VOLUME XLIII NUMBER 6

THE
JOURNAL OF GEOLOGY

August-September 1935

ORDOVICIAN STEWARTVILLE-DUBUQUE PROBLEMS

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ABSTRACT

The Stewartville formation comprises the *Maclurina* zone of the "Galena group" of the upper Mississippi Valley; the Upper *Receptaculites* zone persists in its base. The formation is composed of heavy-ledged dolomite and limestone, the latter predominating northward. The Dubuque formation succeeding it contrasts lithologically in having thinner ledges with shaly partings. The Dubuque dolomite in northwestern Illinois becomes white limestone in northern Clayton County, Iowa; it is the *Oxoplecia* (*"Triplecia"*) zone of Minnesota. Throughout its extent, it is overlain by the *Depauperate* zone of the Maquoketa formation of Richmond age.

Stratigraphic and faunal evidence supports the correlation of the Stewartville with the Upper Cobourg, and the Dubuque with the Collingwood of the standard section. The essential conformity of Collingwood equivalents on the Stewartville and unconformity below Richmond beds in both the Upper Mississippi Valley and northern Michigan favors the classification of the Collingwood in the Mohawkian series and Trenton group. The presence of *Halysites*, *Characloceras*, and other fossils in the Stewartville gives it greater faunal similarity to the Red River formation of Manitoba and the Bighorn dolomite of the West than has been appreciated.

INTRODUCTION

The Stewartville and Dubuque formations are parts of the Ordovician "Galena formation" of the upper Mississippi Valley. The name "Galena" was applied to the "gray, or drab-colored limestone, very friable," a dolomite described by Hall[1] as being exposed at Galena, northwestern Illinois (Fig. 1). The term has been applied variously to beds of several ages and lithologies in the region. The section in which the Galena was first described is illustrated (Fig. 2).

[1] James Hall, in J. W. Foster and J. D. Whitney, "Geology of the Lake Superior Land District," Part II, "The Iron Region," *U.S. 32d Cong., Special Sess.*, Vol. III (1851), Exec. Doc. 4, p. 146.

The names Prosser, Stewartville, and Dubuque were applied by Ulrich in 1911 and Sardeson in 1907 to several parts of the Galena beds. The Prosser (from Prosser's Ravine,[2] west of Wykoff, Fillmore County, Minnesota) "comprising the Clitambonites [Vellamo],

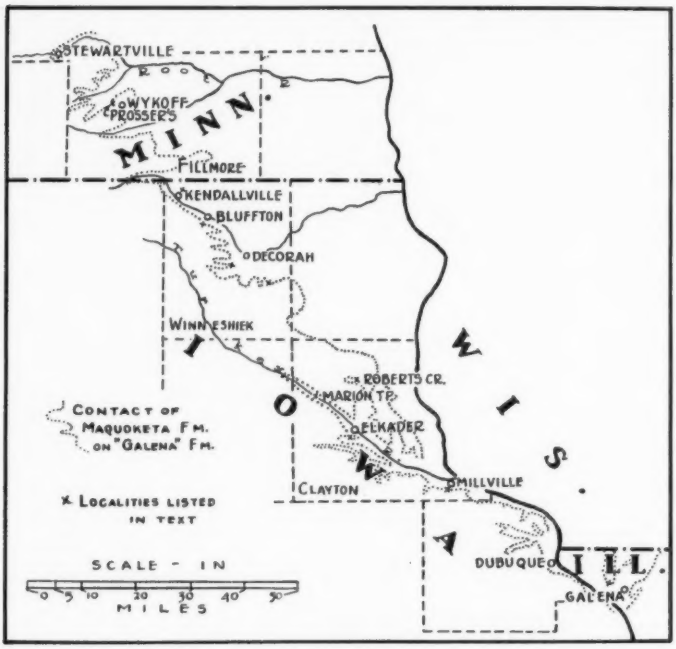

FIG. 1.—Map of localities in the Mississippi Valley along belt of outcrop of the Stewartville and Dubuque formations.

Nematopora, and Fusispira beds of the Minnesota reports,"[3] was shown on a correlation table as being separated from the succeeding Stewartville (Olmstead County, Minnesota) dolomite ("Maclurea bed")[4] by a hiatus. The Dubuque (Iowa) dolomite had been de-

[2] N. H. Winchell and E. O. Ulrich, "Lower Silurian Deposits of the Upper Mississippi Province," *Geol. Nat. Hist. Surv. Minn.* Vol. III, Part II (1894), p. lxxxvi.

[3] E. O. Ulrich, "Bearing of the Paleozoic Bryozoa on Paleogeography," *Geol. Soc. Amer. Bull. 22* (1911), p. 255.

[4] E. O. Ulrich, "Revision of the Paleozoic Systems," *ibid.*, Pl. 27.

fined previously by Sardeson[5] as extending above "the top of the zone of *Maclurea cuneata*, Whitf.—that is, ... the top of the 'cap rock' at Dubuque, Iowa, ... to the blue shales of the Maquoketa proper."

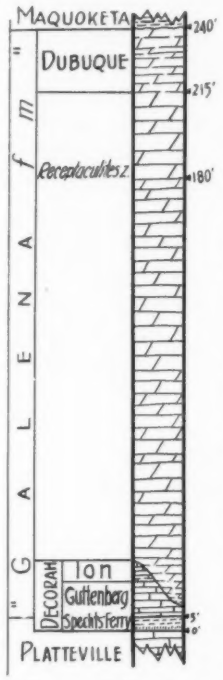

FIG. 2.—Columnar section of the formations outcropping in the extreme northwestern part of Illinois.

Definition of formations.—The Stewartville formation, the "*Maclurea* zone," does not have its limits exposed in its type section. *Maclurina cuneata* (Whitfield), *M.* sp. cf. *M. manitobensis* (Whiteaves), *Maclurites crassus* (Ulrich and Scofield), *Hormotoma major* (Hall), *Fusispira subfusiformis* (Hall), and *Lophospira minnesotensis* Ulrich and Scofield are associates in and adjacent to the Upper *Receptaculites* zone, within which *R. oweni* Hall is abundant. The Stewartville is considered as extending upward from the base of the Upper *Receptaculites* zone, or subjacent ledges containing the *Maclurites* fauna. In the type region of southern Minnesota, the formation is succeeded by the "*Triplecia* zone," characterized by *Oxoplecia ulrichi* (Winchell and Schuchert).

The Dubuque formation comprises the beds succeeding the Stewartville and underlying the Maquoketa shale. The typical Dubuque is the upper 30 feet of "Galena" beds at Dubuque, Iowa; this is a revision of Sardeson's classification of the type section which will be discussed later (p. 571). The Dubuque beds are distinguishable from the subjacent Stewartville in that they are thinner-ledged and contain shaly partings. Of the fossils listed from the Dubuque, *Pseudolingula iowensis* (Owen) has been considered most characteristic. The *Depauperate* zone overlies the typical Dubuque and forms the base of the succeeding Maquoketa formation.

[5] F. W. Sardeson, "Galena Series," *Geol. Soc. Amer. Bull. 18* (1907), p. 193.

PROBLEMS RELATING TO THE STEWARTVILLE AND DUBUQUE FORMATIONS

The stratigraphy of the two formations has a direct bearing on several problems that relate not only to the upper Mississippi Valley but to other areas. There has been difference of opinion expressed with respect to the continuity of the "Galena" beds of northwestern Illinois and southern Minnesota. Similarly divergent views have been given concerning the correlation of the formations with those of the standard section. Their correlation affects the interpretation of the conditions in latest Mohawkian and earliest Cincinnatian time, and thus has a bearing on the proper placement of the line between those series. The classification of the Manitoba Red River formation and its Arctic and western homologues hinges on the classification of the Stewartville, which has a similar fauna. These are the problems that will be discussed in this paper. There are others of similar importance, as for instance those relating to the changes in lithology of limestones to dolomites.

The writer appreciates the suggestions and criticisms that have been received from several geologists, including A. F. Foerste, E. Kirk, F. W. Sardeson, and E. O. Ulrich. The cephalopods listed have been identified by A. K. Miller.

CONTINUITY OF BEDS WITHIN THE REGION

The type section of the Stewartville formation is in Olmstead County, Minnesota, 25 miles north of the Iowa border. That of the Dubuque formation is 140 miles to the southeast opposite the northwestern corner of Illinois. Sections have been described in each of these areas, but divergent opinions have been expressed with respect to their interrelations. This is the problem of continuity of beds within the region.

Southern Minnesota.—The most important "Galena" section in southern Minnesota is that described forty years ago along Prosser's Ravine, 2 miles west of Wykoff, Fillmore County;[6] it is the type section of the Prosser formation, and is illustrated in Figure 3. It shows the relative thicknesses of the formations in the area, and permits the placement of the exposures at Stewartville. The lowest ex-

[6] Winchell and Ulrich, *op. cit.*, p. lxxxv.

posed beds do not extend to the base of the Prosser formation, but include the Lower *Receptaculites* zone which is believed to be about 40 feet from the base. A distinctive horizon is the 11-foot cherty bed about 35 feet higher, within which *Probillingsites* sp. was collected. *Maclurina manitobensis* and the upper zone of *Receptaculites oweni* appear 48 feet above the cherty beds, and the beds become magnesian and show pitted weathering. Specimens of gastropods are frequent through the succeeding 25 feet, and beds of the same lithology extend to the top of the bluff, 108 feet above the cherty beds. Allowing 40 feet for the beds below the Lower *Receptaculites* zone, and making the first appearance of *Maclurina* the base of the Stewartville, the Prosser is about 134 feet thick, the Stewartville, 60 feet.

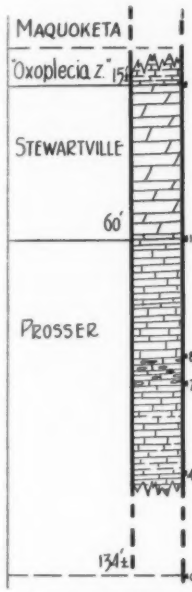

FIG. 3.—Section along Prosser's Ravine, Wykoff, Minnesota.

The next succeeding beds were included in the "Utica Group" by Winchell and Ulrich, and in the "Maquoketa series, Transition formation" by Sardeson;[7] each of the writers considered *Oxoplecia* ("*Triplecia*") *ulrichi* (Winchell and Schuchert) distinctive of the strata. The top of this *Oxoplecia* zone is not exposed at the locality, but the beds are believed to be about 15 feet thick, a thickness that persists in nearby sections. That the *Depauperate* zone of the basal Maquoketa succeeds them as it does in northern Iowa is suggested by the listed occurrence of *Ctenodonta fecunda* Hall from southern Minnesota.

Though both the Stewartville and the *Oxoplecia* zone are composed of limestones, their characters differ sufficiently that they can be distinguished not only in southern Minnesota but in Winneshiek and northern Clayton counties, Iowa. The Stewartville is normally gray or grayish-buff fine-textured limestone in a mesh of buff me-

[7] Sardeson, *op. cit.*; "Galena and Maquoketa Series," *Amer. Geol.*, Vol. XVIII (1896), p. 359; Vol. XIX (1897), p. 24.

dium-textured dolomite; the rock is hard and brittle, and in ledges lacking argillaceous partings. The formation weathers with a distinctly pitted surface (Fig. 4). In contrast, the *Oxoplecia* zone has white, softer limestone in thinner ledges of half a foot or more thick-

FIG. 4.—Upper Stewartville dolomite, showing mottled appearance and pitted character of weathered surface (on left); roadside near head of Prosser's Ravine, Wykoff, Fillmore County, Minnesota.

ness having gray shaly partings that locally constitute a considerable part of the whole; on weathering it forms somewhat nodular blocks with curved surfaces.

Essential conformity of the two formations is suggested by the consistent 14- to 15-foot thickness of the *Oxoplecia* zone in northern Iowa; and no disconformities were observed affecting the top of the

Stewartville. Locally the base of the *Oxoplecia* zone has crinoidal limestones and brachiopod-fragment coquinas, suggesting that it was deposited in shallow water.

The best section at Stewartville is one of 28 feet of dolomite exposed in an old quarry north of the Root River ½ mile west of town (Fig. 5). The presence of many specimens of *Maclurina* in the lowest beds exposed suggests that they are near the base of the Stewartville formation; the upper 10 feet of beds in the quarry are thinner-ledged

FIG. 5.—Old quarry north of Root River ½ mile west of Stewartville, Olmstead County, Minnesota; Stewartville dolomite.

than those below. In 1932, a rock cut was made on the highway in the northern part of the town, the removed material yielding the faunule listed in Table I.

Northern Iowa.—The Upper *Receptaculites* and *Maclurina* beds of the Stewartville have been recognized within the "Galena" formation of northern Iowa.[8] But though the *Oxoplecia* zone was distinguished from the Stewartville by Minnesota geologists, the beds seem neither to have been identified nor specifically separated in northern Iowa, though they are as distinct as in Minnesota.

The thickness of the Stewartville as defined varies from 45 to 65 feet in northern Iowa; the normal thickness is 55 to 60 feet. In the thickest section, along State Highway 9 seven miles southeast of

[8] S. Calvin, "Geology of Winneshiek County," *Iowa Geol. Surv.*, Vol. XVI (1906), p. 94; A. G. Leonard, "Geology of Clayton County," *ibid.*, p. 266.

Decorah, *Receptaculites oweni* is common in beds 61 to 66 feet below the top of the formation, and *Maclurina cuneata* occurs at the base of that zone. Two miles west of the junction of Highways 9 and 55 south of Decorah, *Receptaculites oweni* is common 44 feet from the top of the formation, and *Maclurites crassus* is found within 18 feet of the top. That the lowest observed occurrence of *Receptaculites* and *Maclurina* is synchronous in all sections would be an unwarranted assumption; hence the measured thickness at this locality may be too small. In Section 16, Bluffton Township, Winneshiek County, *Receptaculites oweni* is common 52 feet from the top of the Stewart-

TABLE I

STEWARTVILLE FAUNULE, STEWARTVILLE, MINNESOTA

Ischadites sp. cf. *I. iowensis* (Owen)	f*	*Maclurites crassus* (Ulrich and Scofield)	c
Receptaculites oweni (Hall)	f	*Trochonema umbilicatum* (Hall)	f
Fusispira subfusiformis (Hall)	u	*Charactoceras* sp. cf. *C. rotundum* Troedsson	r
Hormotoma major (Hall)	c	*Endoceras* sp.	f
Lophospira minnesotensis Ulrich and Scofield	u	*Lambeoceras confertum* Foerste	f
Maclurina cuneata (Whitfield)	u	*Westonoceras minnesotense* (Clarke)	c
Maclurina manitobensis (Whiteaves)	c		

* The following abbreviations are used in referring to the abundance of the fossils: "a," abundant; "c," common; "f," frequent; "u," uncommon; "r," rare.

ville; *Maclurites crassus* is common 5 feet, and *Hormotoma major* and *Lophospira minnesotensis* abundant 8 feet lower, giving the formation a thickness of 60 feet. The white medium-textured limestone of the Prosser outcrops 10 feet lower.

One of the best and most accessible exposures of the Stewartville is in the large quarry along Highway 139, ½ mile north of Kendallville, in extreme northwestern Winneshiek County. The rock is mottled white and buff magnesian limestone; the 38 feet 6 inches of heavy ledges exposed do not extend to the base of the formation, but are exposed in contact with the *Oxoplecia* beds at the top of the section. The Stewartville beds in the quarry contain the faunule listed in Table II.

Along Roberts Creek, 6 miles north of Elkader, Clayton County, in Section 14, Wagner Township, the faunule given in Table III is found.

In the northern part of Iowa, the thickness of the *Oxoplecia* zone is consistently about 14 to 15 feet. *Dalmanella* sp. cf. *D. porrecta* (Sardeson), *Sowerbyella praecosis* (Sardeson), and *Pseudolingula* sp. aff. *P. philomela* (Billings) are present in the shales at many ex-

TABLE II

STEWARTVILLE FAUNULE, KENDALLVILLE, IOWA

Halysites gracilis (Hall)	u	*Maclurina manitobensis* (Whiteaves)	c
Streptelasma sp.	f	*Maclurites crassus* (Ulrich and Scofield)	f
Receptaculites oweni Hall	c	*Trochonema umbilicatum* (Hall)	f
Platystrophia sp.	r	*Endoceras* sp.	u
Bucania sp. cf. *B. simulatrix* Ulrich	r	*Lambeoceras confertum* Foerste	u
Bucania sp. cf. *B. subangulata* Ulrich	r	*Westonoceras* sp. cf. *W. Minnesotense* (Clarke)	c
Fusispira intermedia Ulrich and Scofield	f	*Illaenus* sp. cf. *I. americanus* (Billings)	r
Fusispira subfusiformis (Hall)	u		
Maclurina cuneata (Whitfield)	u		

TABLE III

STEWARTVILLE FAUNULE, ROBERTS CREEK, SIX MILES NORTH OF ELKADER, IOWA

Streptelasma sp.	f	*Maclurina manitobensis* (Whiteaves)	c
Receptaculites oweni Hall	f	*Maclurites crassus* (Ulrich and Scofield)	f
Pseudolingula sp.	r	*Trochonema umbilicatum* (Hall)	f
Rafinesquina sp.	r	*Ephippiorthoceras* sp.	u
Ectomaria sp.	r	*Lambeoceras confertum* Foerste	u
Fusispira subbrevis Ulrich and Scofield	u	*Westonoceras minnesotense* (Clarke)	f
Hormotoma major (Hall)	c	*Illaenus* sp. cf. *I. americanus* (Billings)	u
Hormotoma trentonensis Ulrich and Scofield	f		

posures. *Rafinesquina* sp. aff. *R. camerata* Raymond not *Strophomena camerata* Conrad is abundant along the roadside just southwest of Kendallville, with *Dalmanella corpulenta* (Sardeson) *sensu lato*, and rare specimens of *D. futilis* (Sardeson). *Prasopora* sp. and *Pseudolingula iowensis* (Owen) are found with the three widely occurring species first named along the roadside in the southwest quarter of Section 28, Marion Township, Clayton County. In Section 29 of the same township, the *Oxoplecia* zone is exposed for 23 feet above

the Turkey River to its contact with the Maquoketa *Depauperate* zone; *Cyrtodonta* sp. and *Dinorthis* sp. are included in the faunule.

Lenticular, platy limestones intercalated within shales in the *Oxoplecia* beds along Highway 9 seven miles southeast of Decorah (see p. 568) are quite fossiliferous (Table IV).

The *Oxoplecia* zone is succeeded by the Elgin member of the Maquoketa shale, in which the *Depauperate* zone is present at the base in nearly all of the many exposures examined, that just southwest of Kendallville being the exception. The *Depauperate* zone has pyritized specimens of *Orthoceras sociale* Hall and other mollusks in a matrix having phosphatic collophanite pisolites.

TABLE IV

OXOPLECIA ZONE FAUNULE, HIGHWAY 9, SIX MILES SOUTHEAST OF DECORAH, IOWA

Cyclospira sp. cf. *C. bisulcata* (Emmons)	r	*Rafinesquina* sp. aff. *R. deltoidea* (Conrad)	u
Dalmanella sp. cf. *D. porrecta* (Hall)	c	*Sowerbyella praecosa* (Sardeson)	f
Dinorthis sp.	u	*Cuneamya oblonga* Ulrich	f
Platystrophia sp.	r	cf. *Bythocypris* sp.	a
Pseudolingula sp. aff. *P. philomela* (Billings)	f	*Calymene* sp.	f
		Isotelus sp.	c

In summary, in northern Iowa the Stewartville is represented by limestone and dolomite identical to that of the type area of southern Minnesota, having a thickness of about 60 feet. The *Oxoplecia* zone, overlying it, is similarly identical to that of Minnesota, lithologically and faunally, and has a thickness increasing from about 15 feet at the northwest to more than 23 feet in Marion Township, Clayton County.

The Lead and Zinc District.—This area contains the locality from which the "Galena formation" gained its name, and the type section of the Dubuque dolomite (Fig. 2). Whereas the beds differ somewhat lithologically from those of northern Iowa and of southern Minnesota, it is believed that there is sufficient evidence to demonstrate their continuity with the formations farther north.

The section at Dubuque has been published as follows:

	Feet
15. Thin-bedded Galena limestone, earthy, non-crystalline; the layers ranging from ten or twelve inches near the base to less than three inches in thickness near the top; upper part of this member very shaly; carries as fossils *Lingula iowensis*, *Liospira lenticularis* and *Conularia trentonensis*	30
14. Well dolomitized Galena in layers ranging from one to two and a half feet in thickness; with softer beds near the middle, which frequently disintegrate so as to form caverns; basal part only, of this member, represented above the Receptaculites beds at Eagle Point	30
13. Two or three rather heavy ledges containing large numbers of the problematic fossil, *Receptaculites oweni* Hall, Receptaculites is found sparingly in other members of the section. At this horizon, which will be called the Receptaculites zone, it is exceedingly abundant	10[9]

The "cap rock" is in the middle of bed No. 14, and hence Sardeson's typical Dubuque would contain the upper part of bed No. 14 and all of bed No. 15, the *Depauperate* zone of the basal Maquoketa immediately overlying that bed. However, the formation was stated to extend from "the top of the zone of *Maclurea cuneata*." The beds above the "cap rock" in zone No. 14 are structurally and lithologilogically similar to the beds below that bed, as was indicated in Calvin's placement of them. The presence of *Lambeoceras confertum*, a typical Stewartville cephalopod, in the beds above the cap rock in northwestern Illinois[10] further supports the classification of the upper half of zone No. 14 into the Stewartville formation.

Thus the Dubuque dolomite is redefined as restricted to zone No. 15 of Calvin's section, it being the thinner-ledged dolomite with shaly partings overlying the heavy-ledged Stewartville dolomite in the section. The beds are well displayed in the two quarries north of Fourteenth Street at Columbia College in Dubuque, the upper of which is shown in Figure 6. *Pseudolingula iowensis* is common in the lower beds of the formation in the lower quarry; the following

[9] S. Calvin and H. F. Bain, "Geology of Dubuque County," *Iowa Geol. Surv.*, Vol. X (1901), pp. 424–49.

[10] Edwin Kirk, personal communication.

additional species have been collected: *Dalmanella* sp. cf. *D. porrecta* (Sardeson), plates of *Cheirocrinus* sp., *Prasopora* sp., and a branching bryozoan.

Sections in southern Clayton County northwest of Dubuque are similar to that at Dubuque. There is complete exposure of the Stewartville formation beneath the lower Dubuque along U.S. Highway 52, a mile southwest of Millville. The tan, coarse-textured, sparsely fossiliferous, heavy ledges of Stewartville dolomite, 52 feet thick, have a 5-foot bed with *Receptaculites oweni* in their base;

FIG. 6.—Upper quarry in Dubuque dolomite at Columbia College, top of W. Fourteenth Street hill, Dubuque.

Amphilichas sp. is among the species collected immediately above this zone. The Dubuque succeeds without evident disconformity; 16 feet of thin to fifteen-inch ledges of somewhat earthy, plane-bedded dolomite with thin shaly interbeds that contain *Pseudolingula iowensis* and *Dalmanella* sp. are exposed.

In the quarry on the southwest side of the hill just south of Elkader, Clayton County, 24 feet of the Dubuque are overlain by the lowest Maquoketa shales (Fig. 7). The Dubuque is composed of buff to gray, medium-textured magnesian limestones in ledges 6 inches to 1 foot thick; intercalated gray and tan shales are locally very fossiliferous (Table V).

The bryozoa are identical to those occurring in the type Dubuque, and the *Prasopora* sp. seems identical to that collected in the *Oxo-*

plecia beds in Section 29, Marion Township, a few miles to the northwest; preservation of the Elkader specimens is too poor to permit good sections being obtained.

FIG. 7.—Twenty-four feet of Dubuque dolomite underlying the basal Maquoketa shale (at arrow) in quarry in hill southwest of Elkader, Clayton County, Iowa.

Lying on the somewhat ferruginous and pitted upper surface of the Dubuque is an eight-inch bed of brown, gritty, hackly fracturing shale with phosphatic pellets and pyritized mollusks, *Orthoceras sociale* Hall being abundant. This bed, the *Depauperate* zone of the base of the Maquoketa formation, is succeeded by yellow platy siltstone of the Elgin member of that formation.

The floor of the quarry is 130 feet above limestones in which *Receptaculites oweni* is abundant, beneath the bridge west of the quarry. *Vellamo* ("*Clitambonites*") *trentonensis* (Raymond) is present in the limestones 15 feet below this Lower *Receptaculites* zone of the Prosser formation. If the Decorah formation is about 40 feet below this *Receptaculites* zone as it normally is, the Prosser plus the Stewartville has a thickness of about 170 feet in the section. The Elkader section is 7 miles directly south of the Stewartville and *Oxoplecia* zone exposures on Roberts Creek and about 8 miles southeast of the outcrop of the latter beds in Section 28, Marion Township.

TABLE V

DUBUQUE FAUNULE, SOUTHWEST OF ELKADER, IOWA

Cheirocrinus sp. plates and stems	a	*Platystrophia* sp.	f
Prasopora sp.	f	*Pseudolingula* sp. cf. *P. iowensis* (Owen)	u
Ramose bryozoan uniden.	c	*Rafinesquina* sp.	u
Dalmanella sp. cf. *D. porrecta* (Sardeson)	a	*Sowerbyella praecosa* (Sardeson)	u
Dinorthis sp. cf. *D. subquadrata* (Hall)	f	cf. *Cyclendoceras* sp.	r
Hebertella sp.	u	*Calymene* sp.	u
		Ceraurus sp.	u

East of Dubuque, the Stewartville has been faunally recognized in sections in northern Illinois and southern Wisconsin, according to published descriptions. The type of *Maclurina cuneata* (Whitfield) came from Whitewater, Wisconsin. The Dubuque has not been described as occurring east of the Lead and Zinc District, though the available literature is meager. The Stewartville *Maclurina* fauna characterizes the McCune limestone in northeastern Missouri.

Summary and conclusions.—The Stewartville formation is believed continuous and synchronous from the type locality in southern Minnesota to northwestern Illinois. The Dubuque dolomite as redefined seems to be the southern extension of the *Oxoplecia* bed of southern Minnesota and northern Iowa.

With respect to the Stewartville, a zone in which *Receptaculites oweni* is common retains a persistent position in the heavy-ledged upper "Galena" beds through their belt of outcrop in the region (Fig. 8). Although the thickness of massive beds decreases from

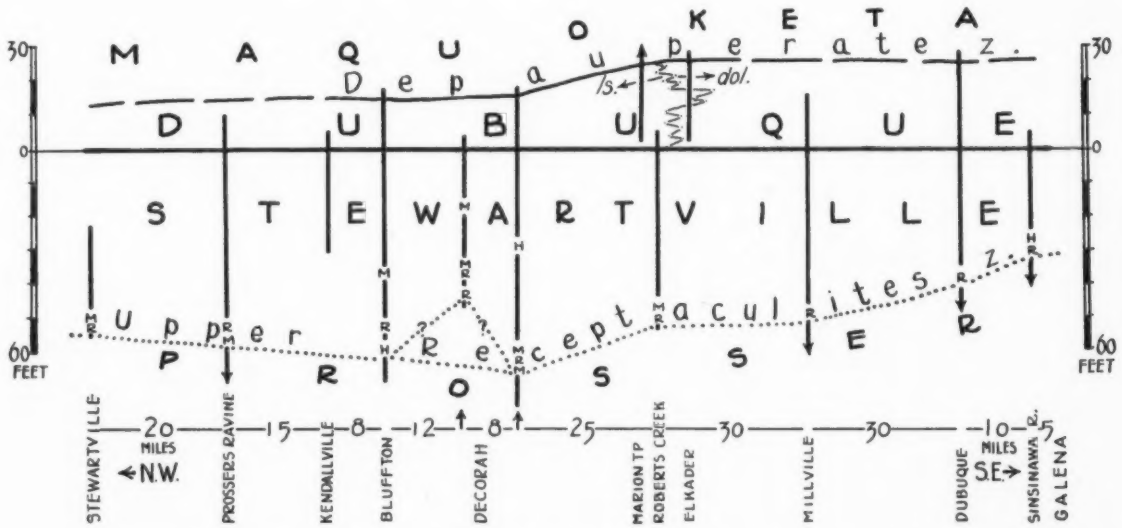

FIG. 8.—Summary of the sections of the Stewartville and Dubuque formations from southern Minnesota to northwestern Illinois. *R—Receptaculites oweni; M—Maclurites* or *Maclurina; H—Hormotoma major.*

about 60 feet in the northwest to some 40 feet at Dubuque, and the lithology is variably magnesian, the change is consistent, and continues into northwestern Illinois, where along the Sinsinawa River the heavy ledges overlying the *Receptaculites* zone are only 30 feet thick. The zone is associated with beds carrying a fauna of gastropods and cephalopods which characterizes the typical Stewartville formation, and which, though most common adjacent to the *Receptaculites* zone, passes into overlying ledges.

In contrast to the Stewartville, the succeeding beds are invariably thinner-ledged and have shaly partings; overlying them there persists the *Depauperate* zone of the Maquoketa formation. In the north these beds are the *Oxoplecia* zone; in the south they have been defined as the Dubuque formation. That they are continuous and synchronous is suggested by their occupying this identical stratigraphic position, and having similar structural characters. It is supported by the fact that the limestone *Oxoplecia* zone increases from 15 feet in southern Minnesota to more than 23 feet in northwestern Clayton County, Iowa; and the nearest exposure of the Dubuque, 8 miles away from Elkader, is of similar thickness that increases to about 30 feet at Dubuque. The faunas are too small, and have too few distinctive common species to alone demonstrate the continuity, but with the collaborating evidence there seems no reasonable doubt that the *Oxoplecia* zone is the northern facies of the Dubuque dolomite.

The Stewartville and Dubuque formations seem essentially conformable. No evidence of erosion of Stewartville prior to Dubuque deposition has been observed. There are suggestions of changing conditions in the more shaly character of the upper formation, and the presence of coarse-textured, coquinal limestones at the base of the Dubuque. The upper surface of the Dubuque represents a considerable hiatus, as is demonstrated not alone by the faunas but by the phosphatic character of the base of the Maquoketa shale.[11] However, the consistent thickness of the Dubuque indicates that there has been little removal of beds by erosion during the hiatus.

The conclusions with respect to the continuity of the Stewartville and Dubuque formations substantiate those reached by geologists

[11] H. S. Ladd, "Stratigraphy and Paleontology of the Maquoketa Shale of Iowa," *Iowa Geol. Surv.*, Vol. XXXIV (1929), pp. 345–49.

at the end of the last century, but questioned in later years. With respect to the Stewartville, the synchroneity of beds in southern Minnesota and northeastern Iowa was clearly believed in by Hall and Sardeson, and by Calvin and Bain.[12] With regard to the correlation of the *Oxoplecia* ("*Triplecia*") zone with the Dubuque, Sardeson has written that the former "is the top 30 feet of the 'Galena' formation at Scales Mound, Illinois, and Dubuque, Iowa."[13]

The fauna of the Stewartville as collected by the writer is given in Table VI.

TABLE VI

STEWARTVILLE FAUNA

Halysites gracilis (Hall)
Streptelasma sp.
Ischadites sp. cf. *I. iowensis* (Owen)
Receptaculites oweni Hall
Platystrophia sp.
Pseudolingula sp.
Rafinesquina sp.
Rhynchotrema sp.
Bucania sp. cf. *B. simulatrix* Ulrich
Bucania sp. cf. *B. subangulata* Ulrich
Ectomaria sp.
Fusispira subbrevis Ulrich and Scofield
Fusispira subfusiformis (Hall)
Fusispira intermedia Ulrich and Scofield
Hormotoma major (Hall)
Hormotoma trentonensis Ulrich and Scofield
Lophospira minnesotensis Ulrich and Scofield
Lophospira sp. cf. *L. bicincta* (Hall)
Maclurina cuneata (Whitfield)
Maclurina manitobensis (Whiteaves)
Maclurites crassus (Ulrich and Scofield)
Sinuites sp. cf. *S. cancellatus* (Hall)
Trochonema umbilicatum (Hall)
Charactoceras sp. cf. *C. rotundum* Troedsson
Endoceras sp.
Ephippiorthoceras sp.
Lambeoceras confertum Foerste
Probillingsites sp.
Westonoceras minnesotense (Clarke)
Amphilichas sp. aff. *A. cucullus* (Meek and Worthen)
Illaenus sp. cf. *I. americanus* (Billings)

Table VII lists the fauna collected in the Dubuque dolomite and the *Oxoplecia* beds.

CORRELATION WITH THE STANDARD SECTION

Having concluded that the Stewartville and Dubuque formations are continuous and distinct within the upper Mississippi Valley,

[12] C. W. Hall and F. W. Sardeson, "Paleozoic Formations of Southeastern Minnesota," *Geol. Soc. Amer. Bull.* 3 (1892), pp. 331–68; S. Calvin and H. F. Bain, "Geology of Dubuque County," *Iowa Geol. Surv.*, Vol. X (1902), pp. 409–11.

[13] "The Galena and Maquoketa Series," *Amer. Geol.*, Vol. XIX (1897), p. 30; "Galena Series," *loc. cit.*, p. 193.

the next problem is that concerning their proper classification with respect to the standard formations of New York and Ontario. Hall stated that the Galena limestone "rests upon fossiliferous strata of the Trenton age," "must be recognized as a distinct member of the Lower Silurian System, which is not recognized in the east," and yet "does not form a series of transition beds between the upper and lower Silurian."[14] During the succeeding half century, it was usually

TABLE VII

DUBUQUE FAUNA

Cheirocrinus sp.
Prasopora sp.*
Branching bryozoan*
Cyclospira sp. cf. *C. bisulcata* (Emmons)†
Dalmanella corpulenta (Sardeson)†
Dalmanella futilis (Sardeson)†
Dalmanella sp. cf. *D. porrecta* (Sardeson)*
Dinorthis sp. cf. *D. subquadrata* (Hall)*
Hebertella (?) sp.
Oxoplecia ulrichi (Winchell and Schuchert)†
Platystrophia sp.
Pseudolingula iowensis (Owen)
Pseudolingula sp. aff. *P. philomela* (Billings)†
Rafinesquina sp. aff. *R. camerata* Raymond†
Rafinesquina sp. aff. *R. deltoidea* (Conrad)†
Sowerbyella praecosis (Sardeson)*
Cuneamya oblonga Ulrich†
Cyrtodonta sp.†
cf. *Cyclendoceras* sp.
cf. *Bythocypris* sp.†
Calymene sp.*
Ceraurus sp.†
Isotelus sp.†

* Occur in both Dubuque dolomite and *Oxoplecia* zone limestone.

† Limited to *Oxoplecia* zone.

considered as of Trenton age, and frequently referred to as the "Galena-Trenton."

As the classification of strata in the Galena and in the eastern Trenton became refined, efforts at precise correlation were begun. Ulrich in 1911 considered the Stewartville to be "Middle Trenton" in age, and the Prosser to be equivalent to beds underlying the "base of the typical Trenton section in New York," and thus to be Hull (Curdsville).[15] Raymond in 1916 stated that the "Stewartville dolomite is not present in Ontario, nor have any of its characteristic

[14] *Loc. cit.*, p. 147.

[15] E. O. Ulrich, "Revision of the Paleozoic Systems," *loc. cit.*, p. 525 and pl. 47.

fossils been found there";[16] in considering the Prosser to range from basal Sherman Fall to top Upper Cobourg in age, he classified that entire formation as younger than had Ulrich, and made the Stewartville post-Cobourg or Collingwood. Ulrich in 1930 correlated the Prosser with the "Trenton group," and in his table had "Galena (age?)" opposite Eden and Maysville in the Cincinnatian.[17] Thus the dolomites in the vicinity of Galena, Illinois, that include Stewartville beds were considered to be post-Trenton in age.

There are several facts that indicate that the Stewartville is of Trenton age, and that it is approximately the correlative of the Cobourg in the standard section. Its lower limit can be defined on stratigraphic evidence. The writer has demonstrated that the upper Decorah (Ion member) is of lower Hull age;[18] quite as satisfactory evidence supports the Rockland age of the middle Decorah (Guttenberg) and the later Hull age of the *Vellamo* zone of the Prosser. Thus the Stewartville as well as the underlying upper Prosser is younger than upper Hull.

This can be substantiated by considering the section in northern Michigan. In that region along the Escanaba River, beds containing *Maclurites crassus* and *Maclurina cuneata* immediately succeed (probably with disconformity) shales having in abundance *Prasopora selwyni* (Nicholson), and *P. oculata* Foord, Sherman Fall bryozoa that are also present in the middle Prosser *Nematopora* beds in Minnesota.[19] That the latter are of lower Sherman Fall age is supported by the presence in them of metabentonites, and by the correlation of the subjacent strata with the Hull. The limestones having *Maclurina* at the base are about 60 feet thick, and thus both homotaxial and of similar thickness to the typical Stewartville. And their uppermost ledges at Bichlers Quarry, on the lower

[16] P. E. Raymond, "Expedition to the Baltic Provinces of Russia and Scandinavia," *Bull. Harvard Mus. Comp. Zoöl.*, Vol. LVI (1916), p. 257.

[17] E. O. Ulrich, "Ordovician Trilobites of the Family Telephidae and Concerned Stratigraphic Correlations," *Proc. U. S. Natl. Mus.*, Vol. LXXVI (1930), p. 73.

[18] G. Marshall Kay, "Mohawkian Ostracoda: Species Common to Trenton Faunules from the Hull and Decorah Formations," *Jour. Paleon.*, Vol. VIII (1934), pp. 328–43.

[19] G. Marshall Kay, "Ordovician Altered Volcanic Materials and Related Clays," *Geol. Soc. Amer. Bull. 46* (1935), p. 238.

Escanaba, are mottled magnesian limestones succeeded by thin beds containing *Pseudolingula iowensis* (Owen), such as occurs in the Dubuque dolomite succeeding the Stewartville in Iowa.

That these 60 feet of limestones are Upper Cobourg is suggested by the character of the faunule in them at Rapid River, Michigan; and at this locality the uppermost shaly limestones again have fossils suggestive of Dubuque. Moreover, Collingwood shales have been reported in the region,[20] and must lie above the limestone. Thus on stratigraphic evidence, the Stewartville must be younger than lower Sherman Fall and older than Collingwood, and be equivalent to late Sherman Fall and/or Cobourg.

With respect to correlation on the basis of fauna, the situation is not as clear. The Stewartville fauna is predominantly a molluscan one, whereas brachiopoda are more prevalent in the eastern Trenton. *Receptaculites oweni* occurs in the Lower Cobourg in New York, but it has a long range in the upper Mississippi Valley and elsewhere. Though the gastropod fauna of the Stewartville is most similar to that of the Upper Cobourg, this may be partially due to the fact that the Upper Cobourg has the one large gastropod fauna in the upper part of the Trenton section. The greater similarity of the Stewartville fauna to the Upper Cobourg fauna than to that of the lower Trenton Hull formation is apparent when the faunas are tabulated (Table VIII).

CORRELATION OF THE DUBUQUE FORMATION

The Dubuque formation has been classified by Ulrich[21] as the oldest formation in the Richmondian, which he places as a lower group in the Medinan series of the Silurian; it is considered a correlative of the basal Queenston shale, which overlies the Lorraine "group" in New York. As has been stated (p. 565), the *Oxoplecia* zone in Minnesota was placed in the "Utica Group" at the base of the Cincinnatian by Winchell and Ulrich, but in the Maquoketa formation by Sardeson.

[20] R. Ruedemann and G. M. Ehlers, "Occurrence of the Collingwood Formation in Michigan," *Contr. Univ. Mich. Mus. Geol.*, Vol. II (1924), No. 2, pp. 13–18.

[21] E. O. Ulrich, "Revision of the Paleozoic Systems," *loc. cit.*, pl. 28; R. S. Bassler, "Bibliographic Index of American Ordovician and Silurian Fossils," *U.S. Natl. Mus. Bull. 92* (1915), pl. 3.

From a stratigraphic standpoint, the Dubuque must be younger than most of the Cobourg, if the Stewartville be of that age; and it underlies the Maquoketa, which is of Richmond age. The formation seems essentially conformable with the Stewartville, but dis-

TABLE VIII

HULL AND UPPER COBOURG GASTROPODS

HULL FAUNULES*	UPPER COBOURG FAUNULES
Bucania intexta Hall	*Clathrospira* sp.
Bucania punctifrons Hall	
Carinaropsis acuta Ulrich and Scofield	
Conularia trentonensis Hall	*Conularia trentonensis* Hall
Cyclonema montrealense (Billings)	*Fusispira subfusiformis* (Hall)
Gyronema sp. cf. *G. semicarinatum* Salter	*Fusispira vittata* (Hall)
Holopea sp. cf. *H. insignis* Ulrich and Scofield	*Holopea ampla* Ulrich and Scofield
Holopea sp.	*Holopea* sp.
Hormotoma alexandra (Billings)	*Hormotoma trentonensis* Ulrich and Scofield
Hormotoma gracilis (Hall)	*Hormotoma* sp. aff. *H. trentonensis* Ulrich and Scofield
Hyolithes sp.	
Liospira vitruvia (Billings)	*Liospira vitruvia* (Billings)
Loxonema murrayana (Billings)	*Lophospira* sp. cf. *L. bicincta* (Hall)
Phragmolites compressus Conrad	*Salpingostoma expansum* (Hall)
Raphistomina lapicida (Salter)	
Scenella compressa Ulrich and Scofield	
Sinuites cancellatus (Hall)	*Sinuites cancellatus* (Hall)
Subulites elongatus (Hall)	*Tetranoda bidorsata* (Hall)
	Trochonema umbilicatum Hall
	Trochonema sp.

* Hull faunules from shore of North Channel, Lot 18, Conc. I, Fredericksburgh South Township; and Lot 14, South shore Conc., Amherst Island, both in Lennox and Addington county, Ontario. Upper Cobourg faunules, several from southwestern Prince Edward County, Ontario, and southwestern Jefferson County, New York.

conformable beneath the Maquoketa. In northern Michigan, beds considered to be Stewartville equivalents are overlain by the Collingwood, and that disconformably by the Richmond. Thus there is similarity in the upper Mississippi Valley sequence to that in northern Michigan.

Faunally the Dubuque has certain species that point toward a late Trenton, Collingwood age. *Oxoplecia ulrichi* is a species of a

genus represented only by *O. calhouni* Wilson in possible correlative formations, and that species is found in the Collingwood. *Cyclospira bisulcata* (Emmons) is most characteristic of the Cobourg, but is represented in Collingwood faunules; it has not been reported from post-Trenton beds. The *Rafinesquina* abundant in the limestones near Kendallville is a distinct species most similar to the species called *R. camerata* by Raymond,[22] from the Collingwood limestone at Craigleith, Ontario. Several species of *Pseudolingula* are common in the Collingwood, and there are similar species in the Dubuque; *Pseudolingula iowensis* occurs in the highest limestone beds in northern Michigan, probably of low Collingwood age. The genus *Cheirocrinus* is long ranging but seems distinctive of the middle Ordovician. Plates of *Cheirocrinus* sp. are abundant in the Dubuque beds at Elkader, Iowa, in limestones adjacent to the Collingwood shale at Rapid River, Michigan, and in the Collingwood shale of Ontario; specimens have been collected from all but the Rockland of underlying Trenton formations of New York and Ontario, however.

The Dubuque formation seems to be of Collingwood age. It lies with essential conformity on a formation that has been correlated with the pre-Collingwood, Upper Cobourg, and occupies a stratigraphic position identical to that of the Collingwood of northern Michigan. Moreover, the faunal evidence supports a view that it is of Collingwood age.

CLASSIFICATION OF THE COLLINGWOOD FORMATION

The Dubuque formation has been correlated with the Collingwood, and thus its classification is dependent on the placement of that division in the standard section. The Collingwood was named by Raymond[23] and at the time made the lower of two divisions of his Middle Ordovician "Utica Group," the upper being later named the Gloucester.[24] The subjacent Upper Cobourg formation ("Upper Picton") comprised the top of his "Trenton Group." Later,

[22] P. E. Raymond, "Contribution to the Description of the Fauna of the Trenton Group," *Can. Geol. Surv. Mus. Bull. 31* (1921), p. 50, pl. 6, figs. 12, 13.

[23] "Trenton Group in Ontario and Quebec," *Can. Geol. Surv. Summary Rept. for 1912* (1914), p. 348.

[24] Raymond, "Correlation of the Ordovician Strata of the Baltic Provinces," *Bull. Harvard Mus. Comp. Zoöl.*, Vol. LVI (1916), p. 254.

Bassler[25] classified the Collingwood as the top of the Trenton, placing the Gloucester (Ontario "Utica") in the base of the Cincinnatian Eden group. Raymond in 1921[26] stated that "the Utica is not considered as a separate unit, but as a shaly phase of the Trenton," and placed the Collingwood in the top of the Trenton group. Ruedemann[27] considered his "Utica Group" to be Cincinnatian and included within it not only the Collingwood and Gloucester but also the Cobourg formations, which he believed synchronous with the older Utica of the Mohawk Valley. Parks[28] expressed it as his opinion that the Collingwood should be classed as Middle Ordovician, and the Gloucester as Cincinnatian.

REGIONAL RELATIONS

In the Mohawk Valley, New York, the Sherman Fall equivalent Canajoharie shale is succeeded by the Lower and Middle Utica; the Upper Utica passes gradationally into the arenaceous Frankfort shale of Eden (Cincinnatian) age[29] (Fig. 9). The principal lithologic changes are at the base of the Canajoharie at its contact with limestones of oldest Sherman Fall age and between the Utica and Frankfort, which intergrade. The Utica is a faunal unit that probably reflects the facies.

Northwest of Utica, the Upper Utica overlaps the Lower Cobourg limestone in central Oneida County. The character of the westward termination of the Lower and Middle Utica, and the appearance of the Lower Cobourg is not evident because of lack of exposure in the drift-covered critical area. The Upper Utica beds have been correlated with Collingwood and Gloucester by Ruedemann; if this is correct, the principal disconformity is pre-Collingwood.

In northwestern New York, the Deer River and Atwater Creek

[25] *Op. cit.*, pl. 2.

[26] "Contribution to the Description of the Fauna of the Trenton Group," *loc. cit.*, p. 1.

[27] "Utica and Lorraine Formations in New York. Part I. Stratigraphy," *N.Y. State Mus. Bull. 258* (1925), p. 149.

[28] W. A. Parks, "Faunas and Stratigraphy of the Ordovician Black Shales and Related Rocks in Southern Ontario," *Trans. Royal Soc. Can.*, 3d ser., Vol. XXII, Sec. 4 (1928), p. 60.

[29] Ruedemann, *op. cit.*

shales lie disconformably on the Upper Cobourg limestone which contains in its upper beds *Ogygites latimarginatus* (Hall).[30] These shales have been classified as Gloucester by Ruedemann, but Sproule[31] states that the "species are all listed from the Collingwood black shales of Ontario."

In Ontario, Parks interprets the Collingwood and Gloucester shales as essentially conformable, but with local disconformity between them. On Manitoulin Island the Collingwood lies with un-

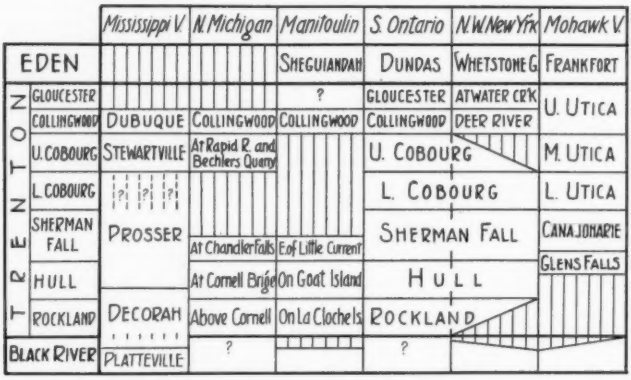

FIG. 9.—Correlation of sections having the Collingwood formation or its equivalents

conformity on the pre-Cambrian and limestone which seems of lower Sherman Fall age; the relationship to the Eden Sheguiandah formation has not been described. The principal disconformity seems to underlie the Collingwood and to be an expansion of the disconformity that in northern Michigan separates Upper Cobourg from lower Sherman Fall. In Michigan, Cobourg and Collingwood beds are succeeded by late Cincinnatian Richmond strata similar to the Maquoketa shale of Iowa; there is great disconformity above the Collingwood, the Eden and Maysville being absent. The Stewartville and Dubuque have been correlated with the Upper Cobourg

[30] G. Marshall Kay, "Ordovician Trenton Group in Northwestern New York," *Amer. Jour. Sci.*, Vol. XXVI (1933), pp. 11–14.

[31] J. C. Sproule, "A Study of the Cobourg Formation," thesis, Univ. Toronto (1934).

and Collingwood, and underlie Maquoketa as do their Michigan equivalents.

In support of the view that the Collingwood is Trenton, strata of this age are conformable to underlying beds in Ontario, northern Michigan, and the Mississippi Valley. Though there is disconformity below them in Manitoulin, it is an overlap of one which in northern Michigan passes below the Upper Cobourg. The fauna of the Collingwood shale is closely related to that of the underlying Cobourg, and that of the Upper Utica to the fauna of the older Utica members; the latter is a reflection of facies, but the former involves comparison of beds of two lithologies. The presence of a disconformity below the Collingwood equivalent Upper Utica and Deer River does not seem concordant with this disposition, but stratigraphic studies of older Trenton formations demonstrated that the area to the east of their outcrop was an intermittently rising arch in Trenton time.

The Stewartville and Dubuque have not contributed evidence bearing on the classification of the succeeding Gloucester. There may be a small disconformity below it in Ontario. Its equivalent in New York, the Atwater Creek shale, grades down into the Deer River, and upward into the Cincinnatian, and similar conformability prevails in the Upper Utica, which seems of Collingwood-Gloucester age. The placement of the Gloucester in the Trenton group would retain in a single series the beds of Utica facies; it is not possible to judge how strongly this facies has been reponsible for the similarity of Collingwood and Gloucester faunas. The top of the Gloucester is everywhere described as grading into Cincinnatian beds, but in New York the principal lithologic changes take place approximately at the top of Gloucester equivalents. The disposition must be somewhat arbitrary and introduce some anomalies. The retention of the Utica shale within a single series seems, with the evidence at hand, sufficient reason for continuing the classification of the Gloucester in the Middle Ordovician, where it was originally placed by Raymond.[32]

With the consideration of the preceding problems, the classifica-

[32] "Trenton Group in Ontario and Quebec," *loc. cit.*, p. 348.

tion of the upper Mississippi Valley Trenton formations is as shown in Figure 10. The classification of the upper part of the Prosser formation has not been established.

CLASSIFICATION OF THE RED RIVER FORMATION

The classification of the Stewartville formation in the standard section is pertinent to the placement of the Red River formation of Manitoba, for whether the two are synchronous or not, the former has a fauna that is most similar to that of the Red River. The cor-

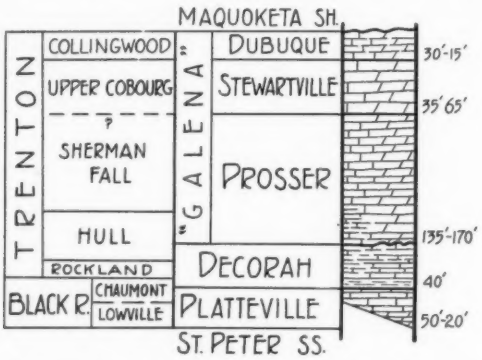

FIG. 10.—Columnar section of upper Mississippi Valley Trenton formations with their classification.

relation and classification of the Bighorn and related formations of Western United States is in turn dependent on the classification of the Stewartville through the Red River, with which the Bighorn seems homotaxial. And the Red River fauna has been recognized in exposures throughout Arctic America.

The Red River problem is essentially of two aspects: first, is some part or all of the formation a correlative of the Stewartville and associated beds? and second, if not, what is its age? "Prevalence of a general Trenton facies suggests its Trenton age. The introduction of characteristic Richmond genera and species suggests its reference to the Richmond."[33] It has also been suggested that "this horizon

[33] A. F. Foerste, "Cephalopods of Southern Manitoba," *Jour. Sci. Lab. Denison Univ.*, Vol. XXIV (1929), p. 146.

was of Cincinnatian age, used in the sense of being pre-Richmond, post-Trenton."[34]

> It is evident that a considerable part of the fauna of the Red River formation shows affinities with the Trenton, especially with the Galena phase of the Trenton. However the direct correlation of the Red River with the Galena . . . . becomes less certain when the cephalopod fauna of the Red River is studied.[35]

The genera *Lambeoceras* and *Westonoceras* were tentatively (and correctly) attributed to the Stewartville fauna by Foerste; the writer's collections have added *Endoceras*, *Charactoceras*, *Ephippiorthoceras*, and *Probillingsites*. Of the 21 genera of cephalopods listed by Foerste, a number are known elsewhere only from supposedly correlative Arctic strata. Others were known to have ranges extending into both Mohawkian and Cincinnatian beds of known classification. The remaining forms Foerste believed to have distinctly Richmond affinities:

> The Maquoketa of Iowa contains *Billingsites* and *Ephippiorthoceras;* also a form that appears identical to *Charactoceras baeri* . . . . originally described from the Richmond of Indiana. Moreover, the Maquoketa contains representatives of the genus *Cyclendoceras* in which annulations are relatively numerous, as in the Red River species *C. whiteavesi.*

Ephippiorthoceras is now known from several Trenton horizons: *E. arcuatum* (Hall) is in the low Trenton (upper Hull or lowest Sherman Fall) at Middleville, New York;[36] *E. sigmoidale* Fritz is common in the Upper Cobourg in Ontario and northwestern New York;[37] and there is a species of the genus in the Stewartville formation. The Stewartville species of *Charactoceras* is "more closely similar and therefore presumably closely related to *C. rotundum* Troedsson of the Cape Calhoun (Greenland) beds than to any other described form";[38] the Cape Calhoun is similar in fauna to the Red River formation. The genus *Cyclendoceras* occurs in the low Trenton at

[34] E. Kirk, "The Harding Sandstone of Colorado," *Amer. Jour. Sci.*, 5th ser., Vol. XX (1930), pp. 464–65.

[35] A. F. Foerste, *op. cit.*, p. 137.

[36] Foerste, "A Re-study of Some of the Ordovician and Silurian Cephalopods Described by Hall," *Jour. Sci. Lab. Denison Univ.*, Vol. XXIII (1928), p. 175.

[37] M. Fritz, in W. A. Parks, *op. cit.*, p. 86.

[38] A. K. Miller, personal communication, 1934.

Middleville, New York, the species being *C. annulatum* (Hall);[39] *C. boreale* Foerste is from an erratic block of supposed Black River age[40] from northern Labrador.

Thus of the cephalopods, *Billingsites* seems to be the single genus that is strongly suggestive of a post-Trenton age for the Red River formation. *Probillingsites* is found in the Stewartville and is common in the Upper Cobourg at several localities in Ontario and New York; it is also present in older formations of Trenton age—in the cherty middle Prosser beds at Prosser's Ravine, Minnesota, and in beds probably of upper Hull age at Cornell, Michigan. The genus is known also in the Meaford (Richmond) formation on Manitoulin Island, Ontario.

With the little information that is published on the cephalopods of the upper Trenton formations, the differentiation of a Richmond or older Cincinnatian cephalopod fauna from one of Mohawkian age is uncertain. The tendency will be to correlate a cephalopod-bearing formation with another in which cephalopods have been found. The character of cephalopods that lived in later Mohawkian time being insufficiently known, it may not be practicable to identify a fauna of that age in possible correlatives.

Of the other classes of organisms in the Red River fauna, the coral *Halysites gracilis* (Hall) has been thought suggestive of a Cincinnatian age, but the species is known to occur in the Stewartville. Of the brachiopods most are characteristic Trenton species and are considerably responsible for the Trenton faunal aspect. *Leptaena unicosta* (Meek and Worthen) seems of Cincinnatian affinity, but the *Rhynchotrema* sp. in the Stewartville is more like *R. capax* (Conrad) than any other Trenton species; and *Dinorthis subquadrata* (Hall) is closely similar to the species in the Dubuque dolomite and to *D. iphigenia* (Billings) of the Lower Cobourg.

One must conclude that the evidence is still not sufficient to demonstrate the age of the Red River unequivocally. Though the

[39] Foerste, "American Arctic and Related Cephalopods," *Jour. Sci. Lab. Denison Univ.*, Vol. XXIII (1928), p. 16.

[40] The writer believes that some of all of the "Black River" beds of the Arctic may be of Trenton age, the genus *Gonioceras* which characterizes them being common in low Trenton strata north of Lake Huron, and present in similar beds in the upper Mississippi Valley and central Ontario.

formation has a close faunal resemblance to the Stewartville, the species in many cases are distinct, and it may be added that forms from supposed Red River equivalents in the Arctic have also been specifically distinguished. There are a few forms that suggest Cincinnatian age, and they may prove to be the most significant, but there are many more that characterize known Trenton formations.

The most definite clue that should be followed is to learn the relative positions of the Red River and Collingwood faunules that have been collected from the vicinity of Cape Chidley, Labrador, and from Countess Warwick Sound, Blunt Peninsula, and Frobisher Bay, Baffin Land.[41] Until some such evidence is obtained, the problem must be considered unsettled, for the faunal evidence seems inconclusive. The facts contributed in this paper lend support to a view that the Red River formation *may be* of Trenton age; and it is possible that the beds represent both the Prosser and Stewartville, the boreal elements appearing in Manitoba in Prosser time, not becoming preponderant farther south until the Stewartville.

CORRELATION OF THE BIG HORN FORMATION OF THE WEST

The correlation of the Bighorn formation of Wyoming is essentially the same problem as that of the Red River. Miller[42] has correlated the Lander sandstone at its base with the Dog Head member of the Red River. He states that "the fauna of the Lower Bighorn, although superficially somewhat similar to that of the Galena, is distinctly younger than it." Forms considered characteristic of the Upper Ordovician such as *Halysites gracilis*, *Paleophyllum stokesi*, *Strophomena planodorsata*, *Dinorthis subquadrata* (*?*) and *Rhynchotrema capax*, included three now known to compose part of the Stewartville fauna.

Kirk has presented evidence which he believes demonstrates the pre-Maysville age of the Lower Bighorn.[43] If the formation is pre-Maysville, and its classification is dependent on the Red River correlation, it likewise might be Trenton.

[41] C. Schuchert, "Notes on Arctic Paleozoic Fossils," *Amer. Jour. Sci.*, 4th ser., Vol. XXXVIII (1914), pp. 469–71.

[42] A. K. Miller, "The Age and Correlation of the Big Horn Formation of Northwestern United States," *Amer. Jour. Sci.*, 5th ser., Vol. XX (1930), p. 211.

[43] E. Kirk, *op. cit.*

SUMMARY OF THE STEWARTVILLE-DUBUQUE PROBLEMS

It has been shown that the Stewartville and Dubuque are continuous formations outcropping from northwestern Illinois into southern Minnesota, and that the Dubuque is represented by the *Oxoplecia* zone in the latter region. The Stewartville has been correlated with the Upper Cobourg formation of the standard section in Ontario and New York; and the Dubuque, with the Collingwood. The seeming conformability of the Stewartville and Dubuque and the considerable hiatus succeeding them support the classification of the Collingwood formation in the Trenton group. The fossils listed from the Stewartville include several found in the Red River formation of Manitoba and Bighorn formation of Wyoming that had not been known to occur in Trenton beds, and suggest that those formations may be of Trenton age.

NOTES ON THE MECHANICS OF ROCK FOLIATION

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ABSTRACT

The present status of the "cleavage" problem in America is briefly outlined, and, using material from a critical area in southern Quebec, the writer applies universal-stage methods to determine the relation of the mineral orientation to the field structures. X-ray data from a slate in the Thüringian Forest support the microscopic evidence. It is concluded that secondary foliated surfaces may have different origins, in some cases being "plaiting" surfaces, in others "shear" surfaces. The relations between the two types are briefly discussed and the importance of petrofabric investigation emphasized.

INTRODUCTION

In the following notes the problem of the mechanics involved in the development of rock foliation is treated and an attempt made to rationalize the seemingly conflicting hypotheses of Leith[1] and Becker.[2] Other investigators have discussed certain aspects of the problem, but there is still little unity of opinion in America. The data presented in this paper will, it is hoped, shed additional light on the problem and co-ordinate to some degree hypotheses already existing. Each represents a part of the truth when viewed in the correct perspective and adds something to the sum total of our information. The following notes are presented therefore in this spirit and with the hope that the methods of investigation used will stimulate further research along these lines.

The work was commenced at Harvard University in 1932 and continued at intervals in 1933 and 1934 in Innsbruck, Göttingen, and Berlin. The writer is indebted to the heads of the mineralogical departments in these schools—Professors Larsen, Sander, Goldschmidt, and Schmidt—for the use of equipment and for helpful advice during the progress of the work. Further acknowledgment is also due Dr. Billings and Dr. Schmidegg for numerous discussions of the problem and to Dr. Labes and Dr. Herrman for assistance in making the X-ray photographs. Critical reading of the manuscript

[1] C. K. Leith, *Structural Geology* (Henry Holt & Co., 1923).

[2] G. F. Becker, "Finite Homogeneous Strain, etc.," *Geol. Soc. Amer. Bull. 4* (1893).

was undertaken by Drs. J. E. Hawley, E. B. Knopf, James Gilluly, W. J. Mead, C. K. Leith, and Andrew Leith, to all of whom the writer expresses his thanks. The material used for optical analysis, collected by the writer and Professor Clark, of McGill University, is the property of the Geological Survey of Canada; that used for X-ray analysis was collected by the writer from the Staatliche Steinbrüche, Lehesten in Thüringen, through the courtesy of the management. For part of the work a universal stage loaned by the Fuess Optical Works was used. All of the work undertaken in Europe was made possible through a Travelling Fellowship granted by the Royal Society of Canada.

PRESENT STATUS OF THE PROBLEM

In schistose, slaty, or gneissic rocks of sedimentary origin the most obvious field observation is the relation of the foliation to the previously existing bedding.[3] Two distinct relationships are dealt with here: (1) foliation developed parallel to the bedding and (2) foliation developed parallel to the axial planes of the folds. Examples of foliation in which no trace of bedding or other primary texture is to be found, or in which there is no symmetrical relationship between foliation and bedding, are also common enough and may be investigated by statistical analyses in exactly the same way as is done for the foliation investigated in this study. The writer proposes to name the first type "bedding" foliation and the second type "axial plane" foliation, since, besides being self-explanatory, both terms are purely descriptive. Bedding foliation may genetically be classified as *primary* (representing recrystallization in situ of grains, particularly mica, which had an initial arrangement parallel to the bedding at the time of deposition), or as *secondary* (representing shearing between beds after their consolidation, with accompanying recrystallization). As will be seen from the following discussion, the latter type of bedding foliation is the one treated here. It is one of the merits of the statistical method of analysis that the mechanical origin of foliation surfaces may be more accurately investigated at present than was formerly possible; hence the need for

[3] All types of parallel texture from the finest slate to the coarsest gneiss are included under foliation as used here.

caution in applying prematurely any term which is not purely descriptive.

Axial-plane foliation has been studied most intensively in the Lake Superior region by the Wisconsin geologists led by Van Hise, Leith, and Mead. It was they who first emphasized the validity of the schistosity-bedding relation expressed by "axial plane" foliation and from the constancy of this relation formulated the useful field criteria, which appear in Leith's "Rock Cleavage"[4] and *Structural Geology*. In explanation of the relation it is assumed that the orientation of the strain ellipsoid to axial-plane foliation is such that the *AB* plane of the ellipsoid is parallel to the foliation, where *A* is the long axis, *B* the mean axis, and *C* the short axis of the ellipsoid. This assumption was challenged many years ago by Becker,[5] who believed that the surface shown by the foliation was parallel, or subparallel, to one of the circular sections of the strain ellipsoid. It should be noted that the "fracture" cleavage of the Wisconsin school is given Becker's interpretation. It is not specifically mentioned in this paper, since none of the data regarding the axial plane and bedding foliations touch it directly. Becker's reasoning, purely deductive and mathematical, made little impression and his paper for the most part has been neglected. The present study bridges these two hypotheses and indicates the probable mechanical difference between axial-plane foliation and bedding foliation.

The application of the strain ellipsoid to bedding foliation has, on the other hand, never been seriously attempted in America, probably because it was of no particular aid in field mapping. In the Austrian Alps, however, Sander[6] and Schmidt[7] have made use of the statistical method of investigating all types of foliation with results which vindicate and supplement Becker's mathematical analysis[8] without, however, disproving the findings of the Wisconsin school. It is now

[4] "Rock Cleavage," *U. S. Geol. Surv. Bull. 239* (1905).

[5] *Op. cit.*

[6] Bruno Sander, *Gefügekunde der Gesteine* (Springer, 1930).

[7] Walter Schmidt, "Gefügestatistik," *Tscherm. Min. Mitt.*, Vol. 38 (1925), p. 392.

[8] It cannot be too strongly emphasized that Sander and Schmidt worked at first entirely without knowledge of Becker's earlier paper. The coincidence of their independent conclusions, approached from both inductive and deductive standpoints, affords, therefore, presumption in favor of their validity.

believed from these inductive statistical studies that foliation may develop either parallel to the *AB* plane of the strain ellipsoid or parallel to the planes of least distortion. There is thus no "cleavage problem" so far as the European workers are concerned. Each case is analyzed on its own merits and interpreted in the light of the orientation data. In America the "cleavage problem" is still a source of contention, owing mostly to non-recognition of all the possible interpretations.

Petrofabric analysis of axial-plane foliation by the newer methods has not been attempted until recently. As representative of the older methods, Leith's microscopic investigation of mineral orientation,[9] made many years ago, was the first detailed study of its kind. It represents, therefore, the first serious petrofabric analysis, apart from the isolated observations of earlier investigators. The newer optic and X-ray methods, developed by Sander and Schmidt in recent years, represent naturally a considerable advance on Leith's pioneer work. In the following pages the writer, by use of these newer methods, presents data which show their usefulness in any consideration of the mechanical origin of bedding and axial-plane foliations.

OPTICAL ANALYSIS OF AXIAL PLANE AND BEDDING FOLIATIONS

The Oak Hill and Sutton formations in southern Quebec furnished the material for optical analysis.[10] The former shows axial-plane foliation and consists largely of fine-grained slaty quartzite schist with interbedded dolomite and graphitic slate. The latter shows bedding foliation and consists of medium- to coarse-grained quartz-sericite-chlorite schist and gneiss with interbedded quartzite, dolomite, and fine graphitic schist. The two formations are separated by a wide band of chlorite schist of extrusive origin which obscures their structural relations.

The material collected from these formations was not intended

[9] "Rock Cleavage," *loc. cit.*

[10] These formations are part of the continuation in Quebec of the Green Mountains belt of Vermont. The Sutton schists form the continuation of the main anticline of the Green Mountains and the Oak Hill (Lower Cambrian) formation lies immediately to the west.

originally for statistical analysis and the geographic orientation of the specimens is therefore lacking. The sections from the Oak Hill formation (axial-plane foliation) are cut normal to the foliation and normal to the general strike of the axes of the folds. The folds pitch only slightly and deviation from exact orientation perpendicular to the axes is not believed to be a serious source of error. In the center of Figure 1, *3*, *b* denotes the projection of the axes of the folds; *A* is a direction in the foliation plane normal to *b; C* is the normal to the foliation plane.

The sections from the Sutton formation (bedding foliation) are cut normal to the foliation and normal to the parallel alinement of the minerals which is commonly seen in the foliation plane. This direction, or tectonic axis, is also denoted as *b* in Figure 1, *5*, and has the same general strike as the axes of the folds of the Oak Hill formation. The letter *a* denotes the direction in the foliation plane perpendicular to *b; c* is the normal to the foliation plane.

In both formations the foliation planes are defined by the parallel dimensional arrangement of flaky minerals such as micas and chlorites. The axial-plane foliation of the Oak Hill formation is, however, less well developed than the coarser-grained foliation of the Sutton formation.

Six of the Sutton formation sections studied are quartz-sericite-chlorite schist with accessory calcite, epidote, magnetite, ilmenite, pyrite, rutile, apatite, and garnet; the seventh is a calcite-quartz-sericite schist. The quartz varies in size from 0.1 mm. to 1.5 mm. in one section of micro-conglomeratic texture. The measured grains average about 0.5 mm. and are for the most part equidimensional. If unequidimensional, the longer dimension is parallel to the foliation plane. Undulose extinction is common, indicating lack of complete recrystallization.

The eight sections studied from the Oak Hill formation are all fine-grained quartz-mica-chlorite schists with accessory feldspar, rutile, apatite, epidote, etc., as with the Sutton sections. Only the largest quartzes could be measured (0.01–0.25 mm. on the average and 0.25–0.75 mm. in one section of conglomeratic texture). The majority are unequidimensional and the longer dimension lies in the foliation plane. These grains, with feldspar and other accessories,

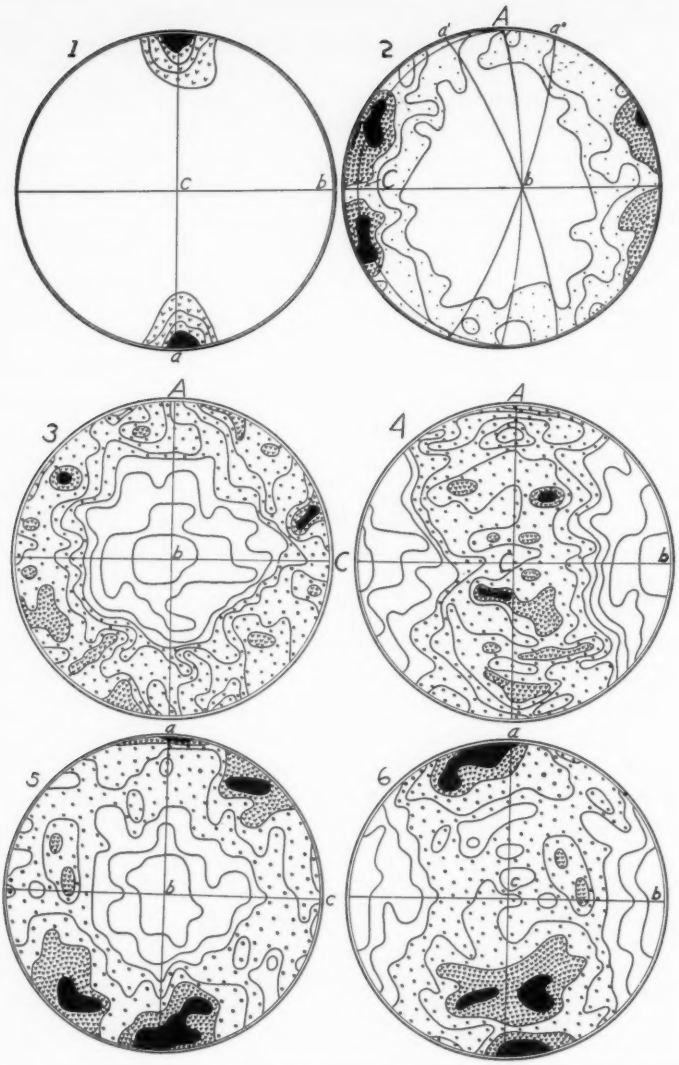

FIG. 1, ILLUSTRATIONS *1–6*. *1*. Schematic diagram to illustrate typical quartz orientation in a zone of intense shearing. *2*. Diagram of 309 poles to cleavages in a crystalline limestone from Tweed, Ontario, to illustrate plaiting surfaces. Contours indicate 6, 4, 2, 1, 0 per cent. *3*. Total diagram of 8 sections of Oak Hill slaty quartzite (axial-plane foliation); 2,547 quartz axes measured. Contours indicate 2, $1\frac{3}{4}$, $1\frac{1}{2}$, $1\frac{1}{4}$, 1, $\frac{3}{4}$, $\frac{1}{2}$, $\frac{1}{4}$, 0 per cent. *4*. Illus. *1* rotated 90° (left to right) about *a*. *5*. Total diagram of 7 sections of Sutton schist (bedding foliation); 2,188 quartz axes measured. Contours indicate 2, $1\frac{3}{5}$, $1\frac{1}{5}$, 1, $\frac{3}{5}$, $\frac{1}{5}$, 0 per cent. *6*. Illus. *3* rotated 90° (left to right) about *A*.

are embedded in a felt of mica, chlorite, and smaller quartzes impossible to measure. Undulose extinction is common in the quartz, absent in feldspar.

The interpretation of the quartz orientation in these two types of foliation depends on the fundamental distinction between "shear" surfaces and "plaiting" surfaces. Briefly, axial-plane foliation represents plaiting in the present study; bedding foliation represents the shear type of surface. Plaiting surfaces form parallel to the plane formed by the greatest and intermediate axes of the strain ellipsoid; shear surfaces form parallel or subparallel to the planes of no distortion. From the standpoint of statistical analysis with the universal stage the distinction between the two types of foliation is made as follows:

Shear surfaces.—Zones of intense shearing, as typified by slickensided surfaces, etc., show particularly accurate lattice orientation[11] of quartz, the most important constituent. The characteristic relation of this orientation to the shear surface is shown in Figure 1, *1*. The plane of the diagram is parallel to the shear surface; the parallel grooves, ridges, etc., in the surface, parallel to which movement is assumed to have taken place, lie parallel to *a*. The statistical analysis of the vertical axes of the quartz shows that they also lie parallel to *a*, with a slight oscillation in the *ac* plane. The interpretation, based on a variety of accessory evidence,[12] is that gliding has occurred in the grains parallel or subparallel to prism faces and in the direction of the vertical axes. Thus we have a direct relation between quartz orientation and the field structure which indicates shearing *in* the foliation surface. This accurate orientation is not typical of all surfaces in which shearing has taken place; as a rule we find a scattering of quartz axes in the *ac* plane of Figure 1, *1*, forming a girdle. The beginning of such a girdle is indicated in Figure 1, *1* by the elongation of the contours in *ac*. There is usually, however, a small majority of axes parallel or subparallel to the foliation surface.

[11] By lattice orientation is meant orientation of crystallographic directions and planes, which in Fig. 1, *1*, is shown by the arrangement of the vertical axes of quartz; in Fig. 1, *2*, by the poles of calcite cleavages. The dimensional axes of the grains may or may not have an orientation correlated to the lattice orientation.

[12] Bruno Sander, *op. cit.*

All stages from the clear case of Figure 1, *1*, to others in which the axes are widely scattered in *ac* are known.

Plaiting surfaces.—In contrast to shear surfaces, a plaiting surface is the result of gliding, or shear movements which take place *inclined* to it. Thus in Figure 1, *2*, are plotted the poles to calcite cleavages from a marble which shows a rough foliation parallel to the plane *Ab* of the diagram. This foliation is caused largely by the parallel arrangement of the longer dimensional axes of the calcite grains. The poles to the cleavages form a girdle as shown. The statistical method brings out, however, that a small majority of the cleavage poles are concentrated in two maxima. The average positions of the two corresponding cleavages are shown by a' and a''. The elongation of the grains (causing the observed foliation) is thus due to gliding, or shearing, along cleavages which have average positions *inclined* to the foliation surface. Actual movement does not occur in *Ab*, and the surface is therefore not a shear surface. Quartz and feldspar may also be "plaited" in the same manner, as shown by examples studied by Leith[13] and Sander.[14]

QUARTZ ORIENTATION

The quartz axes in the sections from the Oak Hill and Sutton formations were measured with the universal stage and the diagrams contoured and rotated in the usual way. The individual diagrams (not published) for each type of schist show marked similarity, and they are therefore summarized for convenience and shown in Figure 1, *3–6* without loss of any important features.

Figure 1, *3*, shows statistically the arrangement of the quartz axes *cv* measured from the Oak Hill slaty quartzite (axial plane foliation) with respect to the three axes *A*, *b*, *C*. *Ab* represents the approximate projection of the foliation plane. It is seen that the area around *b* (direction visible in the foliation plane perpendicular to which the section was cut) is devoid of quartz axes and that the contours form a broad girdle around it. Figure 1, *4*, is constructed from Figure 1, *3*, by rotation of the contours 90 degrees around *A* so that *C* appears in the center and brings out another feature of the quartz, namely, that more axes lie *between* *A* and *C* than *in* *A* or *C*. That is, more axes lie inclined to the plane of schistosity than parallel to it.

[13] "Rock Cleavage," *loc. cit.* [14] *Op. cit.*

Figure 1, *5*, shows the statistical arrangement of the quartz axes measured from the schists of the Sutton formation (bedding foliation) with respect to the three axes *a*, *b*, *c*. The approximate projection of the foliation plane is represented by *ab*. The lack of axes at *b* and the presence of an *ac* girdle is at once apparent and is identical in this respect with Figure 1, *3*. In Figure 1, *6* (rotated 90 degrees around *a*) the distribution of axes in the girdle is seen, however, to differ from Figure 1, *4*, in that a strong submaximum lies at *a* in addition to an area of concentration between *a* and *c*, i.e., a majority of the quartz axes lies parallel or subparallel to the plane of schistosity.

The relation of these statistical data on quartz orientation in bedding and axial plane foliations to shear and plaiting surfaces as typified in Figures 1, *1*, and 1, *2*, is thus fairly clear despite the complex nature of the diagrams. Figures 1, *2*, and 1, *4*, have the common feature that gliding or shear does not occur typically in the observed foliation surface. Therefore, the axial plane foliation represented by Figure 1, *4*, is best classified under plaiting. Figures 1, *1*, and 1, *6*, have the common feature that gliding or shear occurs in large part parallel or subparallel to the observed foliation surface. Therefore, the bedding foliation represented by Figure 1, *6*, is best classified under shearing.

This conclusion is based on the assumption that the gliding in quartz takes place only parallel or subparallel to prism surfaces and in the direction of the vertical axes. Gliding on rhombohedral surfaces inclined 20°–25° to the base is also common, however, and its presence cannot be excluded in this instance since there is no direct control possible from the diagrams. Gliding at least subparallel to prism faces is more common as far as we know at present, and the presence of a minor amount of rhombohedral gliding would not affect in all probability the main conclusion regarding the position of the gliding surfaces of the fabrics represented in Figures 1, *4*, and 1, *6*.

MICA ORIENTATION

Detailed statistical analysis of mica was not made for either type of foliation. In the seven sections showing bedding foliation only a sufficient number of cleavage flakes were measured in order to define clearly the chief foliation plane. The segregation of the flakes into long stringers interwoven between the quartz grains suggests a high

degree of differential movement, or "tectonic unmixing" in *ab*, followed by recrystallization. In the sections showing axial-plane foliation the minute size of the grains made measurement impossible. They show parallel arrangement and localize the foliation plane of the rock. The foliation in general is poorer than that of the bedding type and the mica shows very little evidence of recrystallization. The grains occur commonly as isolated shreds interstitial with quartz and are seldom segregated into long stringers as with the bedding foliation. Their spatial relation to the other minerals suggests a minimum of differential movement or "tectonic unmixing" and indicates that they may owe their present parallel arrangement simply to a dimensional orientation[15] imposed by the deforming forces. This contrast in the mica in the two types of foliation is important and, with regard to the two formations investigated here, may be stated summarily as follows: In bedding foliation the parallel arrangement of the grains is due mostly to differential movement and subsequent recrystallization; in axial-plane foliation it is due mostly to rotation of grains into one surface, with little subsequent recrystallization.

X-RAY ANALYSIS OF AXIAL-PLANE FOLIATION

Additional data were obtained from an X-ray study of roofing slate from a quarry at Lehesten in Thüringen. The material is very fine-grained, homogeneous in texture, and is admirably suited to X-ray investigation. It was collected from a quarry in which the axial-plane foliation relation is well established and specimens were taken in which the bedding-foliation relation was clearly visible. A thin section parallel to the foliation shows a confused mass of brownish-black material, interrupted here and there by unequidimensional nests of clear quartz grains having a common parallel orientation of their longer axes. Accessory magnetite and feldspar are present.

The conditions and set-up for the analysis are as follows: Cu target, KV 30, MA 20, collimator of 2 mm. diameter and 5 cm. length, thickness of sections about 0.35 mm., time of exposure 4 hours on Agfa X-ray film, distance from source of radiation to end of collima-

[15] By dimensional orientation is meant an orientation, by rotation, of grains of heterometric external form so that their longest dimensional axes are in parallel position. This orientation must not be confused with the pseudo-dimensional orientation illustrated in Fig. 1, *2*, which is entirely dependent on the correlated lattice orientation.

tor 10 cm., distance from section to end of collimator 2 cm., distance from section to film holder 4 cm. Under these conditions and with this set-up the most successful photographs were made. Other attempts were less successful.

Symmetry photographs were made from oriented sections and the orientation of the whole mineral assemblage is deduced from the

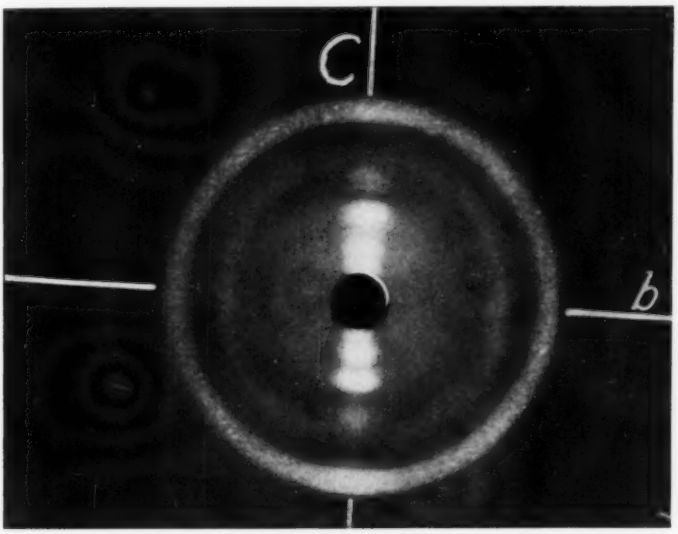

Fig. 2.—X-ray symmetry photograph of Lehesten slate (axial-plane foliation). Section cut perpendicular to foliation and parallel to strike of bedding. Fabric axes as for universal-stage diagrams; *a* perpendicular to plane of photograph.

symmetry of the reflection rings. No attempt is made to identify individual minerals, much less to determine the indices of the reflection surfaces.

Figure 2 shows the symmetry of a section cut perpendicular to the foliation and parallel to the strike of the bedding. All of the visible rings show a concentration of reflections in a north-south direction and indicate that the minerals are oriented. Figure 4 shows the symmetry of a section cut perpendicular to both foliation and strike of the bedding. The evidence of orientation is confined to the

inner rings but is nevertheless clear. Figure 3, cut parallel to the foliation, shows rings in which the reflections are equally strong at all points, indicating therefore no orientation of the minerals. The three photographs combined show that the reflecting surfaces (and therefore the minerals) have an orientation *in* the foliation plane (Figs. 2 and 4), but that in this plane they have no apparent arrangement (Fig. 3). Stated in terms of the rock deformation, there is no lattice

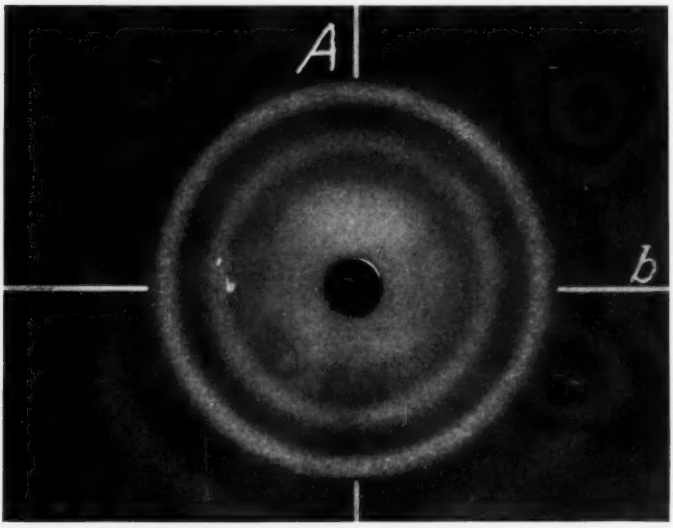

FIG. 3.—Symmetry photograph of Lehesten slate. Section cut parallel to foliation; *c* perpendicular to plane of photograph; *b* parallel to trace of bedding in foliation plane.

orientation, and therefore no evidence of movement parallel to the foliation plane of the slate strong enough to be indicated by an X-ray photograph. The observed slaty cleavage does not represent, therefore, a shear surface since such surfaces show evidence of movement. The cleavage is rather a plaiting surface, parallel to which no movement can take place.

COMPARISON OF DATA ON AXIAL PLANE FOLIATION OF THE OAK HILL QUARTZITE AND LEHESTON SLATE

Figures 1, 4, and 3, are each oriented parallel to a foliation surface and can therefore be directly compared. As none of the reflection

surfaces of Figure 3 show orientation (including those for quartz) there appears to be a difference in the behavior of quartz in the Oak Hill quartzite (Fig. 1, *4*) and the Lehesten slate (Fig. 3). Figure 1, *4*, however, shows no sharp orientation for quartz, although the girdle to be sure is distinct and contains a number of maxima. It is, however, well known that maxima within a girdle, shown by

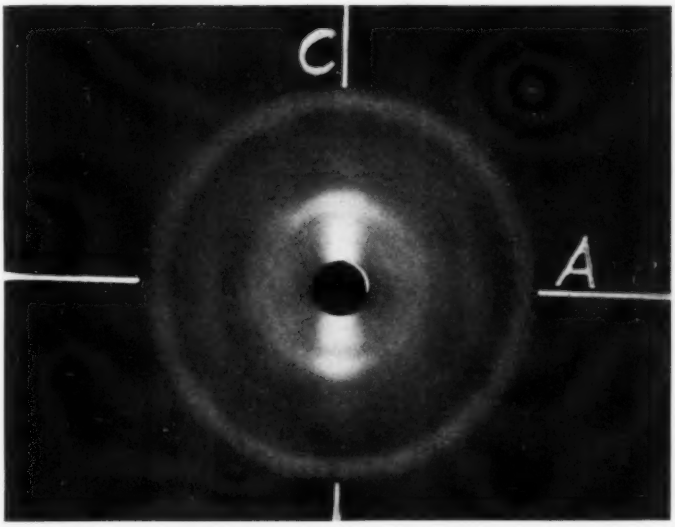

FIG. 4.—Symmetry photograph of Lehesten slate. Section cut perpendicular to foliation and perpendicular to bedding; *b* is perpendicular to plane of photograph.

optical analysis, are not necessarily indicated by X-ray analysis. In other words the X-ray method is less sensitive than the optic method and has its greatest usefulness only in cases in which the orientation is sharp. Furthermore, a recent investigation by Sander[16] indicates that quartz in a very fine state of aggregation is not oriented, whereas mica associated with it shows the usual parallel arrangement. The fact, therefore, that Figure 3 shows reflections of equal intensity at all points on the rings may be important only in connection with the

[16] Bruno Sander, "Typisierung von deformierten Tonschiefern," *Zeit. f. Krist.*, Vol. 89 (1934), p. 97; Sander and Sachs, "Zur röntgenoptische Analyse von Geisteinen," *ibid.* Vol. 75 (1930), p. 550.

mica orientation and have no bearing on quartz orientation. For completeness, the following point in connection with quartz in the Lehesten slate is put on record. Examination of thin sections cut parallel and normal to the foliation shows lens-like nests of quartz grains scattered at intervals throughout the dark, clouded groundmass. These nests have a dimensional arrangement parallel to the foliation and are composed of minute recrystallized equidimensional quartzes. They may represent the granulation and plaiting of single isolated grains and possess a decided orientation. On account of their small size, however, no statistical analysis could be made and their exact significance in relation to Sander's investigation is unknown.

For mica, examination of the Oak Hill quartzite schist sections (without universal stage) shows a probable dimensional orientation; examination of the Lehesten slate with X-rays shows a similar dimensional orientation parallel to the foliation surface, but without evidence of movement parallel to this surface. Possible corroboration of this conclusion is to be seen optically in the quartz nests described above. In a section parallel to the foliation there occur minute unoriented flakes of mica in these nests, which, if their lack of parallel orientation can be correctly ascribed as due to the main deformation, bear out the conclusion reached from the X-ray analysis. From the main groundmass of the slate sections no observation of this nature is possible.

In summary, the orientations shown by quartz and mica, the chief constituents of the Oak Hill schist and Lehesten slate, are not contradictory and consist for quartz of lattice orientation of the majority of axes along gliding surfaces *inclined* to the foliation surface, for mica of a dimensional orientation *parallel* to the foliation surface.

APPLICATION OF STRAIN ELLIPSOID TO AXIAL PLANE FOLIATION

From the above study, optic and X-ray, of quartz and mica in the two types of rocks showing axial plane foliation it is possible to state in general the relation of the conventional strain ellipsoid to the foliation. For the platy minerals (represented chiefly by mica) a dimensional orientation is indicated, which means that such grains

lie mostly parallel or subparallel to the plane of the ellipsoid containing the greatest (A) and intermediate (B) axes. As these grains form the foliation of the rock and this foliation is of the axial-plane type the orientation of the AB plane of the ellipsoid into parallel position with the foliation plane is justified. This bears out the conclusion reached long ago by the Lake Superior geologists as a result of their field work.

The case for quartz gives further information concerning the application of the strain ellipsoid to axial-plane foliation. The optic analysis indicates translatory movements along surfaces in the grains, which surfaces lie inclined to the foliation plane formed by the micaceous minerals. Each translation surface lies as nearly parallel as possible to the planes of no distortion of the strain ellipsoid, and, as Figure 1, *4*, shows, their orientation varies within fairly wide limits. It may therefore be thought that the position of the AB planes of these ellipsoids also varies within fairly wide limits. The following factor in particular favors an average position for AB parallel to the foliation plane. A majority of the quartz grains are unequidimensional and the longer dimension in all cases lies parallel to the foliation plane. This would suggest at first a dimensional orientation as with mica were it not for the evidence of the orientation of the axes given in Figure 1, *4*. This is a case of a pseudo-dimensional orientation in which the grains have probably been lengthened parallel to the foliation plane by translation on crystallographic surfaces inclined to this plane (Figure 1, *2*), giving the effect of true dimensional orientation. Thus it is probable that, despite the scattering of the quartz axes in the girdle, AB is parallel to the foliation plane.

The position of the strain ellipsoid, therefore, as indicated by the orientation of the micaceous minerals and quartz is in general similar to that postulated by the Lake Superior geologists from field and experimental grounds. The writer wishes, however, to emphasize that it is in reality misleading to set up one fixed ellipsoid to represent the strain in the rock unit under consideration. This is especially true with respect to the planes of no distortion of the ellipsoid. The present study shows that the quartz axes are scattered

considerably and that therefore no one fixed position for these planes of no distortion can be set. The orientation of the ellipsoid is therefore limited to the setting-up of its AB plane parallel to the foliation plane of structure, with its B (mean axis) probably parallel to the axes of the folds.

APPLICATION OF STRAIN ELLIPSOID TO BEDDING FOLIATION

From the optical study of quartz and mica in the Sutton formations it is likewise possible to state in general the relation of the strain ellipsoid to the foliation. The flaky minerals, notably mica, determine the foliation surface. The quartzes show a lattice orientation, indicating translatory movement parallel to prism or rhombohedral planes. This translation, in the majority of the grains, took place parallel or subparallel to the foliation surfaces of the rock. From analogy with many other known examples (Figure 1, *1*) this bedding foliation represents, therefore, a plane of least distortion of the strain ellipsoid. No definite statement can be made concerning the AB plane and therefore no fixed position of the strain axes with relation to the planes of least distortion can be postulated.

The situation with regard to Becker's mathematical treatment of strain[17] now becomes clearer. Shear surfaces represent surfaces parallel to which the maximum movement has occurred during a deformation and, in a strain ellipsoid, are equivalent to the planes of least, or no distortion. Minerals showing lattice orientation demonstrate this principle and the example of bedding foliation considered here is therefore best explained by Becker's hypothesis. On the other hand, the axial-plane foliation investigated in this study is best explained as being parallel to Ab of the strain ellipsoid, with movement occurring in surfaces inclined to it. Becker's hypothesis still applies but not with respect to the observable foliation surfaces which lie parallel to the axial planes of the folds. His hypothesis is sound but his attempt to apply it as a direct explanation of all types of foliation surfaces has created confusion. As this preliminary study

[17] *Op. cit.*

shows, modern statistical methods will help to solve these problems and thus remove some of the misconceptions and misinterpretations which are prevalent at the present time.

RELATIONS OF AXIAL PLANE AND BEDDING FOLIATIONS

Field data of the Oak Hill and Sutton formations do not permit any conclusion to be drawn regarding the relations of axial-plane foliation and bedding foliation. As far as the writer is aware, the question has never been satisfactorily answered; indeed, its existence as an unsolved problem has been unrecognized by many investigators. We are, however, accumulating a body of facts concerning this and related problems with which better to approach their solution. As pure hypothesis, it is held by a number of workers in Europe that axial-plane foliation may arise as an early stage of deformation of sediments and that bedding foliation is a later development. Although no proved case of a transition between the two types is known to the writer, the conception is not without value. It is entirely possible, for instance, that an early-formed axial-plane foliation should become the locus of later shearing movements, and that with continuing deformation the bedding should approach parallelism with the shearing direction by a combination of slicing and rotation. At an advanced stage all trace of the earlier folded structure is obliterated and the remaining primary structures, bedding, etc., lie parallel to the former axial-plane foliation, now shear surfaces, and here called bedding foliation. It is furthermore true that axial-plane foliation usually occurs in relatively fine-grained rocks which show a low grade of metamorphism. Bedding foliation, on the other hand, is associated as a rule with medium-to coarse-grained rocks, which show in many cases a relatively high grade of metamorphism. From this standpoint, therefore, the hypothesis of transformation of axial-plane foliation to bedding foliation might receive support.

In addition to this specific problem, there comes up the whole question of the relation between mineral orientation and the *initial* folding, fracturing, and shearing of sedimentary rocks. These are problems of the future and will require careful investigation. The

data presented here cover only one phase of the field, are admittedly far from complete, and the interpretation may need revising as new studies are made. The acceptance, however, of the methods and technique used in petrofabric work interests the writer at present more than the acceptance of any hypothesis. It is quite true that the optical method is time-consuming and that the X-ray method is costly; on the other hand, by the use of these methods a mass of information is obtained which has already proved its worth and which has revealed, to mention the field of structural geology alone, many new points of view and possibilities of practical application.

THE MINERALOGICAL CLASSIFICATION OF IGNEOUS ROCKS: A COMPARISON OF RECENT PROPOSALS

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ABSTRACT

Twelve of the more recent proposals for the classification of igneous rocks are discussed with the intention of noting points of agreement and of difference. A considerable measure of agreement is found regarding the main factors that should be used in classification, but there are serious differences in detail. Can these differences be reconciled?

The twenty years from 1913 to 1933 have produced just twenty proposals for the classification of eruptive (or igneous) rocks. We seem in danger of being snowed under with classifications, just as we have been snowed under with rock names. Some of the twenty schemes are purely chemical—that is, they are based on bulk analysis—others attempt to combine chemical with mineralogical and textural data; but twelve of the twenty are purely or predominantly mineralogical and to a greater or less extent quantitative. The authors of these twelve schemes are:

J. P. Iddings (1909, 1913)[1]
A. N. Winchell (1913)[2]
F. C. Lincoln (1913)[3]
S. J. Shand (1913, 1914, 1917, 1927)[4]
A. Holmes (1917)[5]
A. Johannsen (1917, 1919, 1922, 1931)[6]
E. T. Hodge (1924, 1927)[7]

[1] J. P. Iddings, *Igneous Rocks*, Vol. I (1909); Vol. II (1913).

[2] A. N. Winchell, *Jour. Geol.*, Vol. XXI (1913), p. 208.

[3] F. C. Lincoln, *Econ. Geol.*, Vol. VIII (1913), p. 551.

[4] S. J. Shand, *Geol. Mag.*, Vol. X (1913), p. 508; Vol. I (1914), p. 485; Vol. IV (1917), p. 463; *Eruptive Rocks* (London, 1927).

[5] A. Holmes, *Geol. Mag.*, Vol. IV (1917), p. 115.

[6] A. Johannsen, *Jour. Geol.*, Vol. XXV (1917), p. 63; Vol. XXVII (1919), p. 1; *Descriptive Petrography of the Igneous Rocks*, Vol. I (1931).

[7] E. T. Hodge, "Univ. Oregon Pub., Geol. Series," Vol. I (1927), p. 133.

F. H. Hatch and A. K. Wells (1926)[8]
G. W. Tyrrell (1926)[9]
P. Niggli (1931)[10]
F. F. Grout (1932)[11]
A. Lacroix (1933)[12]

The position would be highly discouraging, were it not that close inspection of the twelve proposals reveals a certain measure of agreement regarding the factors that should be used in classification. The outstanding factors used by the various authors are discussed below.

I

Geological occurrence and texture.—Three divisions—plutonic, hypabyssal, and volcanic rocks—are recognized by Winchell, Hatch and Wells, and Tyrrell. Other authors make only the fundamental distinction between well crystallized and ill-crystallized rocks. The general opinion seems to be against the use of geological criteria in a mineralogical classification, although a division of "dike rocks" will no doubt continue to be recognized by geologists for their own purposes.

II

The *color index*, or ratio of dark to light minerals, is used quantitatively by Lincoln, Johannsen, Niggli, Grout, Lacroix, and the writer. Unfortunately, there is a marked difference of opinion, not only about the limits of the groups, but even about the meaning to be attached to the words "light" and "dark" or "leucocratic" and "melanocratic." The writer, in introducing the term "color index," made it clear that his real intention was to express the ratio of light weight to heavy-weight minerals. Since most of the heavy minerals are dark in color, and all the light minerals are pale in color, it follows that the color index expresses both the appearance and the relative density of a rock. For the writer, therefore, the light minerals are those with density less than 2.8, that is, quartz, tridymite,

[8] F. H. Hatch and A. K. Wells, *A Text Book of Petrology* (1926).

[9] G. W. Tyrrell, *Principles of Petrology* (1926).

[10] P. Niggli, *Schweiz. Min. Pet. Mitt.*, Vol. XI (1931), p. 296.

[11] F. F. Grout, *Petrography and Petrology* (1932).

[12] A Lacroix, *Bull. Serv. géol. de l'Indochine*, Vol. XX (1933), p. 15.

feldspars, feldspathoids (not including melilite under this term), and primary calcite if there be such a thing. Lacroix agrees with the writer in this matter, and so do Lincoln and (apparently) Grout. But Johannsen and Niggli use the words "leucocratic" and "melanocratic" more literally, and include among the former muscovite, scapolite, melilite, topaz, corundum, apatite, andalusite, sillimanite, fluorspar (and formerly tourmaline too).

As regards numerical ratios, we find the differences given in Table I. Objection has been taken to the limits introduced by Johannsen, on the ground that they divide the field unequally. To this one might add that very few rocks hold less than 5 per cent of light minerals (especially in Johannsen's sense of the term). Boundaries at 10 and 90 per cent give a better distribution; but in view of the overwhelming predominance, among granitic rocks, of those with a color index between 5 and 15, it seems very undesirable to put a boundary in this position at the *light* end of the series. At the *dark* end a boundary at 10 or 12 per cent is a reasonable limit for pyroxenites and peridotites.

TABLE I

Lincoln	...	...	33	..	67	..	...
Shand	...	...	30	..	60	..	90
Johannsen	5	...	...	50	...	..	95
Niggli	12½	25	37½	50	62½	75	87½
Grout	10	...	...	50	...	..	90
Lacroix	5	...	35	..	65	..	95

Again, a boundary at 50 per cent is definitely undesirable because, as Grout points out, it has the effect of splitting the gabbros, dolerites, and basalts in the very region where they are most thickly clustered. But a boundary at 30 or 35 per cent (say one-third) separates all the common granites and tonalites from the rare, highly micaceous or hornblendic varieties of these rocks; it also separates the common syenites from the rare shonkinites, the anorthosites from the normal gabbros, and the common foyaites from the rare malignites. Another boundary at about 60 or 65 per cent (say two-thirds) separates the common gabbros and basalts from the less common pyroxenitic gabbros and picrites.

Although all such limits are unnatural, it seems to the writer that

boundaries at about one-third, two-thirds, and nine-tenths of dark minerals fit in better with existing rock names, and with one's impression of the average rock, than any other boundaries. Lincoln, Niggli, Lacroix, and the writer are roughly in agreement on this point.

The proposal to distinguish diorite from gabbro by the color index rather than the composition of the plagioclase is found in the systems of Lincoln and Lacroix as well as in that of the writer. It had the approval of that very high authority, Joseph Barrell. H. S. Washington[13] has used the same method to distinguish andesite from basalt, the former containing more than two-thirds, the latter less than two-thirds, of normative plagioclase. Washington's practice is almost identical with that of Lincoln and Lacroix, and but slightly different from that of the writer.

III

The *degree of saturation with silica* was employed by the writer in 1913. It had previously been recognized by Zirkel and his predecessors in the separation of feldspathic from feldspathoidal and olivine-free from olivine-bearing rocks, but under Rosenbusch these sharp distinctions tended more and more to disappear. The writer carried the matter a little further than Zirkel had done, by showing that other minerals besides those named are incompatible with free silica under magmatic conditions, and by insisting on the theoretical importance of the phase-boundaries between quartz and the various "unsaturated" minerals. At the risk of being tedious, one must make a further attempt to demonstrate the importance of these natural boundaries.

Figure 1 is a reproduction of Bowen and Andersen's diagram for the system MgO–SiO_2. From liquid mixtures in the region *A*, cristobalite and clino-enstatite are the phases that crystallize out on cooling; from liquids in the region *B*, clino-enstatite and forsterite are formed; in the region *C*, forsterite and periclase are the solid phases. The composition line at 60 per cent SiO_2 is a phase-boundary for cristobalite and forsterite, for on one side of this line cristobalite cannot form and on the other side forsterite cannot form. Similarly the composition line at 43 per cent SiO_2 is a phase-boundary for

[13] H. S. Washington, *Amer. Jour. Sci.*, Vol. V (1923), p. 469.

periclase and clino-enstatite. Now, if we had a series of rocks containing only the components MgO and SiO_2, we might classify them from either of two standpoints. From the standpoint of analytical chemistry, we should fix our attention on the percentage of MgO or SiO_2, and we should put our boundaries in such positions as to divide the rock series into convenient sections; they might, for instance, be placed at 25, 50, and 75 per cent of SiO_2. But from the standpoint of physical chemistry, these divisions would be meaning-

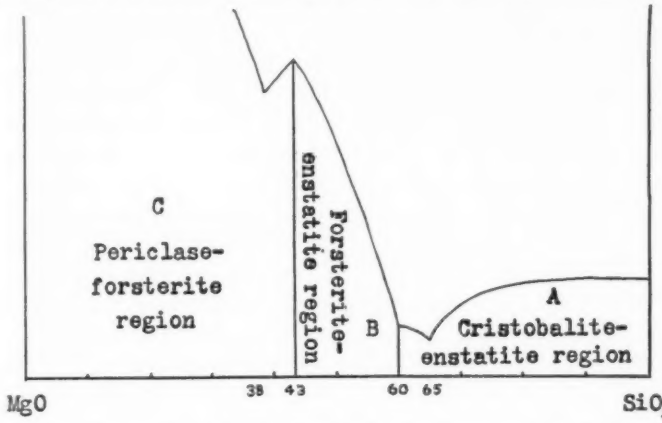

FIG. 1.—The system MgO–SiO_2 (simplified), after Bowen and Andersen. (*Amer. Jour. Sci.*, Vol. XXXVII [1914], p. 488.)

less, and the only significant breaks in the series are those at 38, 43, 60, and 65 per cent of SiO_2, the first and the last representing the two eutectics and the other two the phase-boundaries. It would not be easy to recognize the eutectic mixtures, in the imaginary series of rocks; but it would be perfectly easy to recognize the phase-boundaries and to classify the rocks as oversaturated with silica (region *A*), exactly saturated (the boundary at 60 per cent), undersaturated with silica (region *B*), or oversaturated with magnesia (region *C*). Such a classification would be a truly scientific or natural one, since it conforms to natural boundaries.

It is surprising to find that many petrologists have expressed vague aspirations toward a classification by "eutectic ratios," and

that they yet remain blind to the phase-boundaries which have an equal theoretical importance and are so much more directly applicable to the purposes of classification!

The writer's proposal for the classification of rocks according to the degree of saturation with silica was adopted by Holmes (1917), Tyrrell (1926), Hatch and Wells (1926), and Hodge (1927).

IV

The *composition of the feldspar* is taken into account in one way or another in every classification, but the method varies greatly. Iddings, Winchell, Hatch, Johannsen, Tyrrell, Grout, and Niggli use the actual feldspar developed in the rock. Lacroix uses the normative feldspar. Holmes calculates feldspathoids and micas into their equivalents of orthoclase and albite; thus "orthoclase" and "albite" in Holmes's system do not always represent actual minerals. Hodge goes still further in this direction, for all potassic minerals are reckoned as orthoclase, all sodic minerals (except soda-pyroxenes and soda-amphiboles) are reckoned as albite, and melilite and haüyne (in part) are reckoned as anorthite. The writer employs the feldspar actually present in the rock, but expresses it, for systematic purposes, in terms of the pure components Or, Ab, and An.

Johannsen has criticized the writer's proposal on the ground that it introduces the normative instead of the modal feldspar. This is not strictly correct, for the writer recognizes only the feldspar molecules that are *actually present as feldspar* in the rock,[14] whereas the normative feldspar may include potash, soda, and lime that do not form feldspar in the rock. It is true that the writer's method would put a rock containing soda-orthoclase and a little andesine on the same footing as one containing oligoclase and a less sodic orthoclase; but a similar error is made by every petrologist who states the *average* composition of a zoned plagioclase. One cannot express everything in a rock name; something must be left out, to be sought in the detailed description of the rock.

The writer has previously pointed out that the placing of "orthoclase" (containing a variable proporton of albite molecules) in opposition to "plagioclase" (also containing a variable proportion of

[14] Except, of course, in the case of cryptocrystalline and glassy rocks.

albite molecules) is illogical and unsatisfactory. He believes that the method he has advocated is more exact and leads to more consistent results.

V

The grouping of the dark silicates according to the *ratio of alumina to bases* was developed by the writer in 1927. Four "types" were recognized, which were characterized as peraluminous, metaluminous, subaluminous and peralkaline, respectively; they correspond to different stages in the "reaction-series" of Bowen, and one might call them "reaction types." The advantage claimed for this grouping is that it brings all the dark silicates, which in other systems are treated as so many entirely independent factors, into four groups, within each of which the characteristic minerals have something in common as regards both chemical composition and conditions of formation. The subaluminous type is developed when the magma is hot and relatively anhydrous; the metaluminous type arises from it at lower temperature; the peraluminous and peralkaline types are contrasted products developed in the later stages of crystallization, when the magma is relatively cool and the concentration of fugitive constituents, or "hyperfusibles," as Bowen calls them, is high.

Critics of the writer's system have been silent about the merits or demerits of this proposal. If the writer may take upon himself the rôle of critic, he would point out that the boundaries between the four types are sometimes rather indefinite. Does the presence of a few scraps of biotite in a dolerite demand its removal from the subaluminous to the metaluminous type? Does the slightest mantle of soda-diopside around the augite crystals call for the admission of the rock to the peralkaline type? These are difficulties of the same order that are met in every mineralogical classification, and they must be met in the same way. One speaks of a gabbro as being "transitional toward diorite"; so one may say that a rock is subaluminous but transitional toward the metaluminous or peralkaline type. A more difficult case, which the writer has already encountered in some foyaites from Nyassaland, is that in which aegirine is associated with much biotite. A little biotite is a common reaction product of aegirine; but in these rocks both minerals are present in large quantity.

The biotite is always an iron-rich variety; so the association is definitely peralkaline.

The writer believes that the recognition of the "reaction type" is an important step in classification, and he is encouraged by the appearance of a somewhat similar proposal in the classification of Lacroix. The peraluminous and peralkaline types of the writer have been recognized by Lacroix, but the metaluminous and subaluminous types are replaced by a magnesian and a calcomagnesian type. Lacroix's types may be preferable from the point of view of bulk-chemistry, but they ignore the reaction relation which is recognized in the writer's system. For instance, biotite rocks and olivine rocks fall together in Lacroix's magnesian type, although olivine is at the beginning of the reaction series and biotite at the end of it. Similarly Lacroix's calcomagnesian series includes diopside rocks, diopside-hornblende rocks, and hornblende-biotite rocks, which represent three different stages in the reaction series. It seems that Lacroix has adopted the viewpoint of analytical chemistry rather than that of physical chemistry.

VI

For further subdivision than is afforded by the application of the five factors discussed above, some authors have made use of arbitrary divisions based on the ratio of quartz to feldspar, feldspar to feldspathoid, pyroxene to olivine, silicates to ores, and so on. Johannsen and Niggli have gone farther than others in this direction, each of them setting up an elaborate framework with many arithmetically defined compartments. There is no reason why people should not subdivide as much as they please, for their own purposes; but there is a danger of overdoing it in a classification that is meant for the use of others. As the author of *Moby Dick* wrote, "It is by endless subdivisions based upon the most inconclusive differences that some departments of natural science become so repellingly intricate."

The writer feels that great detail is neither necessary nor desirable in a classification of rocks. If a name indicates the degree of crystallization, the state of saturation with silica, the average composition of the feldspar or feldspathoid, the color index, and the reaction type, that should be sufficient for almost every purpose. Any person who

wishes further particulars about the rock will naturally turn to the detailed description or the chemical analysis. Too much emphasis on mere arithmetic is as bad as none at all, it yields a census, not a natural classification.

SUMMARY

1. There is a strong majority of opinion in favor of two, rather than three, textural divisions as a basis of classification.

2. There is a general desire to recognize the color index in classification, and it should not be difficult to come to some agreement regarding the most suitable limits; but it will be necessary to reconcile divergent opinions about the meaning of the terms "light" and "dark."

3. There is a strong feeling in favor of using actual, instead of calculated, feldspar whenever it can be done, but there are differences of opinion about the method to be followed.

4. The degree of saturation with silica is observed strictly by some petrologists but with much laxity by others, who adhere to the Rosenbusch tradition. The strict observation of phase-boundaries would involve some concession by the latter party, but it would be a concession to physical chemistry.

5. Some systematic method of grouping the dark silicates, whether by recognition of "reaction types" or otherwise, seems to be desirable.

The writer hopes, by means of the foregoing notes, to stimulate interest in, and discussion of, the really urgent problem of rock classification.

THE VALLEY OF GRIMES CREEK IN THE PAYETTE CANYON, IDAHO[1]

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ABSTRACT

Grimes Creek, a tributary of the Boise River, flows in a narrow, groove-like valley parallel to the South Fork of the Payette River for nearly 3 miles apparently along the upper canyon slope and about 1,800 feet higher than the river. The stream was originally a tributary of the Payette River. After tilting of the peneplaned surface, it was captured by a tributary of the Boise River, which worked headward toward the axis of the uplift. Following this stream capture, the region has undergone further uplifting, accompanied by warping, faulting, and tilting of crustal segments; and the present intricate deep canyon system has been carved thereon. Tilting of a segment of the old erosion surface in the downstream direction of the Payette River greatly increased that river's cutting power and permitted it to entrench far below the level of Grimes Creek. The divide between the parallel portions of river and creek has been shifted nearly to the creek, and thus the south side of Grimes Creek valley has become essentially the upper slope of the Payette canyon. Grimes Creek thus flows within the Payette River canyon, but at a much higher level and not in topographic conformity with the major stream.

INTRODUCTION

Far back in the mountainous area drained by the Boise and Payette rivers in southwestern Idaho, Grimes Creek, a tributary of the Boise, flows for some distance in a narrow groove or trench high along the side of the Payette River canyon. The relationship is so extraordinary that it is here presented for interpretation. The valley of Grimes Creek is about 36 miles northeast of Boise, the state capital, which lies on the Snake River Plain at the margin of the mountainous area. Its precise location may be observed in Figure 1, where the course of the creek is parallel to that of the South Fork of the Payette River, not more than a mile and a half away.

PHYSICAL SETTING

The mountains of this part of Idaho are of the dissected-plateau type and comprise an upland surface deeply incised by the trunk streams and most of the larger tributaries. The upland consists of broad, flat-topped ridges and low, rolling hills separated by shallow

[1] Published by permission of the director of the U.S. Geological Survey and the director of the Idaho Bureau of Mines and Geology.

valleys apparently carved in an old peneplaned surface prior to the uplift which initiated the present intricate canyon system. The remnants of this upland do not reach a uniform level but, in the area

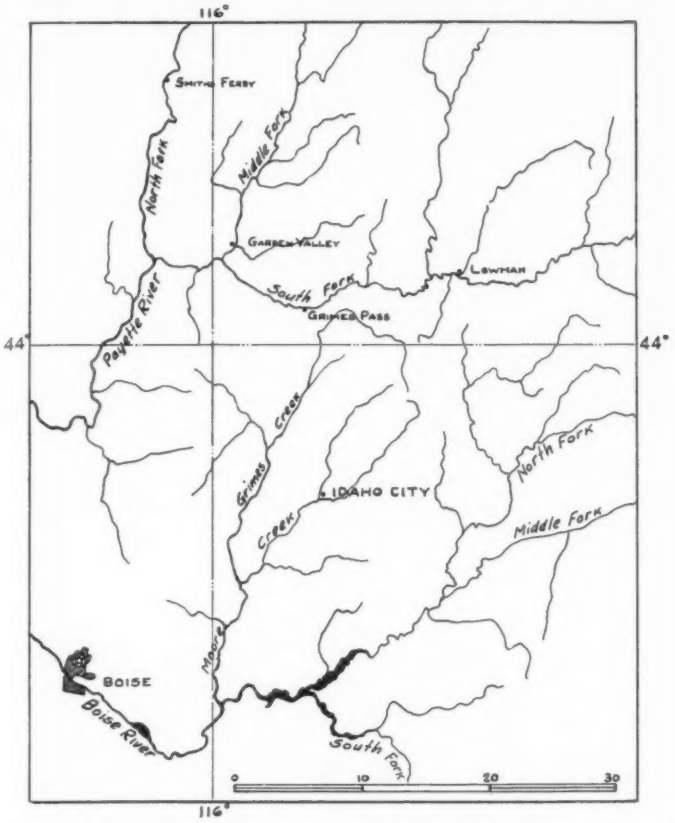

FIG. 1.—Sketch map showing the course of Grimes Creek in relation to the South Fork of the Payette River and the Boise River. Sketch also reveals the unsymmetrical pattern of the two drainage systems, each with the major tributaries entering from the north.

under discussion, lie at altitudes of from 3,000 to above 8,000 feet A.T., and appear as moderately tilted and, in places, as faulted slopes.

FIG. 2.—Topographic map showing the position of Grimes C

ch apparently within the very wall of the Payette Canyon

Across this mountain complex the westerly or west-southwesterly flowing rivers—the Payette on the north and the Boise and its several main branches on the south—have cut narrow canyons, in places more than 4,000 feet deep. The courses of these trunk streams are independent of the different levels of the old upland surface and cut across high and low land alike.

Drainage patterns of each of the two major drainage systems are highly unsymmetrical or one-sided. Tributaries of each reach far to the north (Fig. 1); and those of the Boise River actually head at the very brink of the canyon carved by the South fork of the Payette River, whereas Grimes Creek apparently actually flows within the canyon itself. As these streams are cutting largely in the massive granitic rock of the Idaho batholith, bedrock has had little influence on the drainage pattern and the stream control must be ascribed to other causes.

PAYETTE CANYON

The canyon of the South Fork of the Payette River, here simply designated as the "Payette canyon," extends in a general westerly direction through the mountains; but locally where it contains Grimes Creek (Fig. 2), it has a southwest direction alined with and controlled by a prominent fracture zone. Above the part shown on the topographic map (Fig. 2), the canyon is one of the deepest and most rugged in Idaho, and its sides slope steeply upward to altitudes more than 4,000 feet above the river. Beginning near the east margin of the map, however, the upland surface bordering the canyon descends rather sharply; and where the river leaves the map area, the canyon is only about half as deep as above. As the river continues in a northwesterly direction to Garden Valley, a prominent structural basin produced by faulting,[2] its canyon continues to decrease in depth and cross section and disappears altogether on reaching the floor of the structural depression (Fig. 3), only to reappear across the high ridge on the west side as rugged and almost as deep as before. Changes in the canyon depth are clearly dependent on the altitude of the upland surface, and the decrease in depth to Garden Valley conforms with a westerly tilt of the summit surface which

[2] A. L. Anderson, "A Preliminary Report on Recent Block Faulting in Idaho," *Northwest Science*, Vol. VIII (1934), p. 230.

descends at a moderate angle to, or nearly to, the floor of Garden Valley (Fig. 3). Although the depth of the canyon decreases nearly 2,000 feet in 6 miles, as shown on the topographic map, the river falls only about 115 feet over the same distance or flows from an altitude 3,360 feet down to about 3,245 feet A.T.

FIG. 3.—Picture from the low divide between Grimes Creek and the South Fork of the Payette River, showing the increasing shallowness of the Payette Canyon as it extends northwesterly down the tilted old erosion surface to Garden Valley. The high ridge in the background is bounded by a fault scarp against whose base the erosion surface in the foreground has been tilted and along which Garden Valley has been formed as a structural basin.

A profile of the canyon is shown with the topographic map in Figure 2. It is not complete, for only the south side of the canyon has been mapped from the bottom to the top. The bottom of the canyon is fairly wide; and the river has cut a narrow, gorgelike channel from 50 to 100 feet deep in the canyon floor. The slopes rise steeply from the canyon bottom to the top and are irregularly incised by the tributary gulches. The only abnormality is the terracelike flattening high up the south slope on which Grimes Creek flows in a shallow, essentially one-sided valley.

GRIMES CREEK

Grimes Creek heads on Summit Flat, one of the largest remnants of the old upland surface between the Boise and Payette rivers, at an altitude between 8,000 and 8,500 feet A.T. It meanders through a broad, shallow valley for 3 miles directly toward the Payette River and then curves and flows northwestward for 6 or 7 miles in air line to the edge of the Payette canyon. After leaving the lower end of Summit Flat, its valley deepens, but the bottom remains fairly wide and the stream relatively quiet to the very border of the map area, where the gradient begins to steepen and the valley to become much deeper and narrower, entrenched 500–700 feet below the summit surface. The valley continues to deepen to the margin of the Payette canyon; and the valley floor to decrease proportionately in size, the flats in places disappearing altogether. After apparently entering the Payette canyon the stream curves to the southwest and flows parallel to the river for nearly 3 miles, most of the way from $1\frac{1}{4}$ to $1\frac{1}{2}$ miles from the river and from 1,900 to 1,600 feet above it. Its alinement in the canyon is by the same system of fractures which controls the course of the river. At Grimes Pass the stream leaves the canyon by a much sharper turn than that by which it entered, and flows directly south to the broad depressed area in the mountains known as "Boise Basin." It crosses the basin in a low, wide valley and enters a deep canyon below, eventually uniting with Moore Creek to flow to the Boise River.

Its valley in the Payette canyon strongly suggests a man-made or "high-line" ditch. From below it appears as an indistinct line marked by a somewhat denser timber growth, in places invisible altogether. From the opposite canyon wall the valley resembles a ditch carved high up the slope, as shown in Figure 4. From above on the ridge top, the valley of Grimes Creek is wholly lost from view, and the floor of the canyon and the river appear natural, with no indication whatsoever of Grimes Creek.

It is evident that this valley is the stream's own making. Its floor is like that above its entrance to the canyon, and the stream for part of the distance is bordered by narrow flats. Its gradient conforms with that above the canyon, and the stream descends from an

altitude of 5,175 to 4,800 feet as it flows approximately 3 miles parallel to the river. The slope bordering the stream on the southeast is about as steep as the lower part of the Payette canyon and rises as high as 1,700 feet above the stream bed. This slope appears to fit the canyon as well as the valley of Grimes Creek. The ridge above, like the stream, extends parallel to the river. Its crest descends rather steeply; and the ridge ends near Grimes Pass, where

FIG. 4.—A picture of the south wall of the Payette Canyon showing the trench-like valley of Grimes Creek apparently suspended high on the upper slope, 1,600–1,900 feet above the river.

Charlot Gulch joins Grimes Creek. Charlot Gulch, on the south side of the ridge, has a westerly direction and near its mouth is pointed toward Garden Valley and the Payette River.

The low, narrow divide between Grimes Creek and the Payette River is perhaps the most striking feature of the valley. The crest of this divide lies from 200 to 500 feet from the creek and ranges from 70 to 200 feet above. It is lowest where the valley enters and leaves the canyon, and little additional erosive work would be necessary to divert the stream at either place. Placer miners have placed ditches and pipe lines along the divide and occasionally allow the

water from Grimes Creek to spill into the Payette River. An examination of the photograph of Grimes Pass where the creek turns from the canyon (Fig. 5) shows the characteristics of the divide. The slope between Grimes Creek and the low divide is short and steep, and conforms exactly to the lower slope on the opposite side. The slope between the divide and the Payette River is even steeper, and erosion on it is obviously shifting the divide nearer and nearer the

FIG. 5.—A picture of Grimes Pass, showing the low divide separating Grimes Creek from the deep Payette Canyon immediately beyond. At this point the stream turns from the Canyon and flows south to the Boise River.

creek. Today the divide is so close to the creek that the valley slope bordering Grimes Creek on the southeast appears to conform with the slope made by the river on the north side of the divide.

INTERPRETATION

That upper Grimes Creek was once tributary to the Payette River is strongly implied in the stream pattern. The fact that the stream heads not far therefrom and flows directly and then diagonally toward the river and finally parallel to it, where both are controlled by the same fracture zone as far as Grimes Pass, is highly

indicative. Charlot Gulch, its principal tributary, is likewise pointed toward the Payette River, and, if projected, would probably join the Payette near the upper side of Garden Valley. Both, however, are turned abruptly away as though beheaded by some northward-reaching stream from the Boise River that had worked far back into the Payette River drainage, a relation that is strongly implied in the pronounced unsymmetrical pattern of the Boise River drainage with its principal tributaries heading at the very brink of the Payette canyon. It would further appear that after the drainage had become established along the present lines the region was uplifted and the Payette River was deeply entrenched in its present canyon, while Grimes Creek, because of its long distance from the Boise River, was unable to lower the valley at a similar rate and was left far behind and high above. As the Payette River deepened and widened its canyon, it cut back the divide separating it from Grimes Creek, until now Grimes Creek appears in a trench-like valley on a narrow terrace suspended high on the canyon slope. Inasmuch as the Payette River is still vigorously deepening and widening its canyon, it is certain to undermine Grimes Creek valley completely in no great lapse of time and to regain its former tributary.

HISTORICAL SUMMARY

To trace through the development of the course of Grimes Creek, it is necessary to go back to an early date when the Payette and Boise drainages had reduced the region to a broad peneplain, and the trunk streams and tributaries occupied very wide featureless valleys separated by low divides. The main streams probably crossed the lowland in about the same directions, or in the same courses, as today; and the tributaries were perhaps more or less symmetrically arranged about each, with the two main systems equally balanced. Moderate uplift at the north beyond the investigated region, accompanied by southward tilting of the peneplaned surface, then apparently rejuvenated the drainage and caused the trunk streams to entrench in their present courses, which were probably about parallel to the axis of uplift. At the same time the tilting caused a complete rearrangement of the minor drainage to flow in the direc-

tion of the dip of the surface, perpendicular to the axial line, in a manner outlined by Campbell[3] many years ago. This tilting produced southward-flowing tributaries which entered the trunk streams at nearly right angles. As the Boise River tributaries continued to reach northward up the tilted slope, they shifted the divide between them and the Payette drainage nearer and nearer the main Payette River, producing the present one-sided unsymmetrical stream pattern. Finally, one of the Boise River tributaries (Grimes Creek) reached nearly to the Payette River and captured one of the northwestward-flowing tributaries of the latter, diverting it into the Boise. By that time the streams were incised several hundred feet in the tilted surface, having carved most of it into low, rolling hills, although the deep canyons had not yet been produced. But before the threatened Payette River itself became tapped by the encroaching Boise drainage another more complicated and higher uplift disturbed the drainage and inaugurated the present deep canyon system.

The new disturbance or uplift was accompanied by warping, faulting, and local tilting of the fault segments; but it is not the purpose of this paper to trace through the many adjustments made to these later movements. The Boise River canyon system was carved in the generally uplifted old land surface; but deepening in response to this uplift as yet has not extended to the headwaters of all the longer tributaries, of which Grimes Creek is a noteworthy example. Even today Grimes Creek, near its source, occupies the old valley produced after the earlier tilting. The Payette River was also greatly affected by the more recent disturbance, and particularly by the normal or block faulting at the west side of Garden Valley, which caused a sharp tilting of the old land surface from the high country on the east to the level of the structural basin in the direction of the river flow. This tilting of the land surface greatly increased the gradient of the Payette River and provoked deep canyon-cutting; whereas Grimes Creek, because of its affiliation with the distant Boise River, was not so materially affected by the uplift and

[3] M. R. Campbell, "Drainage Modifications and Their Interpretations," *Jour. Geol.*, Vol. IV (1896), pp. 567–81, 657–78.

tilting and continued on as before, with only moderate deepening. Grimes Creek was thus left far behind; and as the Payette rapidly entrenched far below the level of the creek, it cut back the divide between them until that divide has almost disappeared and the south side of Grimes Creek valley has become essentially the upper slope of the Payette canyon. By this action, the creek now flows in a narrow groove or trench high in the Payette River canyon.

A REINTERPRETATION OF THE STILLWATER DEEP-WELL RECORDS

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ABSTRACT

A recent study of the samples from the Stillwater deep well of 1889 shows that the log has been misinterpreted. To further clarify the record, a 20-foot shaft was sunk adjacent to the well and the section carefully studied. The results show a normal Lower Paleozoic section without faulting.

INTRODUCTION

Over a period of years several very important wells have been drilled in and around Stillwater, Minnesota. The chief interest in these wells lies in the great thickness of pre-Cambrian rocks penetrated and in the interpretation placed on the samples from the Paleozoic portion of the hole. The first of these is known as the "Stillwater deep well," and its log has been much discussed for more than forty years. It still remains the deepest well drilled within the state.

Early in 1888, when oil and gas production was spreading through Pennsylvania, Ohio, and other east central states, the idea of valuable fields in the midwest fired the minds of some enterprising citizens of Stillwater. Consequently a stock company of local men was organized for the purpose of investigating the underlying rocks of the region, especially with reference to the possible occurrence of natural gas.

The site chosen for the test is on the edge of the buried preglacial valley that cuts through the city and enters the St. Croix River from the west. It is near the center of block 21, which lies between North Fourth and North Fifth Streets, and is bounded on the north by West Mulberry Street and on the south by West Myrtle Street. The well is thus a block and a half west of the city water works office building. The elevation of the ground at that location is now 780 feet A.T., which is somewhat greater than at the time of drilling, because the well site has undergone extensive grading and filling at a more recent date. Mr. Paige Guthrie of Pittsburgh, Pennsylvania,

was engaged as contractor, and spudded in on June 22, 1888. The work was continued throughout the balance of the year and into the following, when a depth of 3,500 feet[1] was attained. In passing through the Cambrian sandstones, great quantities of water were encountered but no gas or oil. The well, which was cased for 710 feet, to the base of the Hinkley sandstone, was finaly plugged back to the base of the Franconia sandstone and has since become the chief source of water supply for the city. Even now it is one of the finest flowing water wells in the whole artesian basin.

INTERPRETATION OF THE LOG

The drillers took a small number of samples; and these were examined by A. D. Meeds, then a student under Dr. C. W. Hall, and now city gas inspector in Minneapolis. On April 2, 1889, Meeds presented a paper before the Minnesota Academy of Natural Sciences entitled "The Stillwater Deep Well."[2] He confined himself chiefly to a description of the samples and did not attempt to assign them to definite formations, although he did state that he regarded the first twenty samples, or a depth of 717 feet below the drift, as belonging to the Paleozoic and the remainder to the Keweenawan.

Probably the first attempt to assign the samples to formations was made in 1911 by Hall, Meinzer, and Fuller,[3] who summarized and condensed Meeds's description but apparently did not examine the original samples. Various others[4] have followed Hall, Meinzer, and Fuller in their interpretation of the Stillwater log; so there is grave danger that the formational division suggested by them will be generally accepted and the errors perpetuated. Some of these errors should have been apparent from the first. Others only lately have become evident. The correlation that was suggested by these authors in 1917 implies most unusual structural conditions at that

[1] N. H. Winchell, *Geol. Nat. Hist. Surv. Minn. Bull. 5* (1889), p. 27 n.

[2] *Bull. Minn. Acad. Nat. Sci.*, Vol. III (1891), pp. 274–77; Winchell, *op. cit.*, pp. 25–27.

[3] *U.S. Geol. Surv. Water Supply Paper 256* (1911), p. 366.

[4] F. W. Thwaites, *Wis. Geol. Surv. Bull. 25* (1912), pp. 19, 59–60; *Geol. Soc. Amer. Bull. 42* (1931), p. 741; Frederic Bass, Adolph F. Meyer, and Sven A. Norling, *Rept. Water Supply Comm. Minneapolis, June, 1932*, p. 166; Hugo R. Kamb, *Artesian Water for Minneapolis, Minnesota, Report of Layne-Northwest Company* (August, 1932), Pl. opp. p. 29.

locality. Since faulting is known to have occurred in the Upper Mississippi and St. Croix valleys, naturally it has been called upon to explain the supposed anomalous condition in the well. Recently, however, the elevation of the Jordan-Oneota contact has been established, by plane-table, throughout the Stillwater region, with the results shown in Table I. From the gradual rise of the Jordan-Oneota contact through these various points, as shown by the table, it is evident that the fault hypothesis is not supported. Moreover, the pit adjacent to the 1889 well shows the contact at the normal elevation for that point, and thus casts grave doubt on the interpre-

TABLE I

Location	Elevation A.T. in Feet
a) Stairway below McNaughton Quarry ..... (This may be slightly in error but not more than 1 foot)	759.01
b) Wolfe Brewery and the gas tank ..... (Sharp contact)	763.74
c) Pit or shaft adjacent to 1889 well ..... (Sharp contact)	770.84
d) Twin City Foundry and Carli Quarry ..... (Sharp contact)	788.92
e) Boom Hollow, 3 miles north of Stillwater ..... (Sharp contact)	843.34

tation of the whole upper portion of the log. During 1933 two sets of samples from the Stillwater deep well were discovered in the attic of Pillsbury Hall, and a restudy of the material in both sets has since been made. This has led to very different structural conclusions than those commonly assigned to the Stillwater region.

Although the statement is somewhat ambiguous, Meeds seems to have called attention to two intervals of the same thickness at the top of the well. One of these is given as drift and the other is the "coarse, yellow sand consisting of rounded grains of quartz," which constitutes the first sample. According to Meeds, this latter occurs below the drift and is part of the 717 feet which he regards as belonging to Paleozoic rocks. In the interpretation of the log given by Hall, Meinzer, and Fuller, this statement was disregarded and the 18 feet of coarse, yellow sand was placed in the drift. Also, the 20 feet of "very fine-grained and almost pure white sand" constitut-

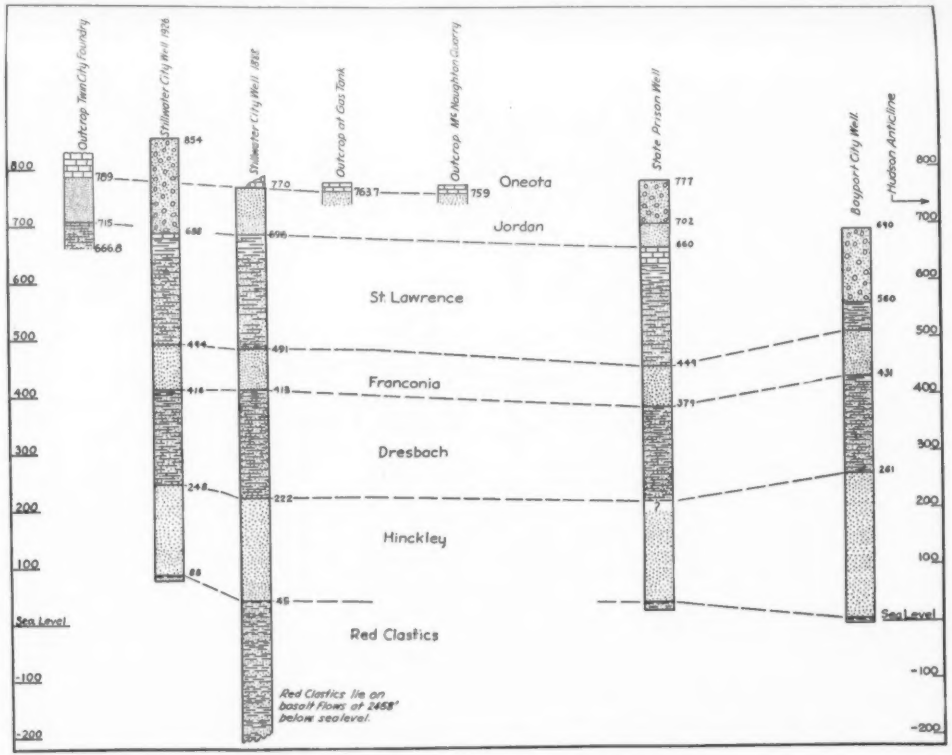

FIG. 1.—Cross section through Stillwater to Bayport, showing correlation of wells and outcrops. Horizontal scale, approximately 4 inches to 1 mile.

ing the fourth sample was increased to 27 feet, and no reason assigned. This latter does not check with the original record or with the labels on either set of samples, and is regarded as an error.

It is quite evident that the samples were taken at irregular intervals and without much regard for the slight changes in sedimentation which are known to occur frequently in the Cambrian and older rocks of the region. According to Meeds, a sample such as the second seems to represent 85 feet of rock; but the label on the official sample, that is the one belonging to the set bearing the University of Minnesota Museum number, and the copy of the same in the Register of the General Museum,[5] indicate that this sample was taken at 103 feet. Likewise, each of the other samples was taken at the depth indicated by the right-hand column of Meeds's section. A chemical and petrographic study of this second sample shows that it is a fine-grained argillaceous to siliceous gray dolomitic shale with some quartz—very different from the Oneota to which it was referred by Hall and others. In fact, it checks exactly with a sample collected from the trilobite bed (Lodi shale) of the St. Lawrence formation in the Boom Hollow section, 3 miles to the north. Hence that member of the formation lies 103 feet below the level at which the drill struck bedrock. The type of rock penetrated between 18 and 103 feet is, therefore, entirely unknown, except as inferred from outcrops of the immediate vicinity, but is not the same as that represented by the second sample. Statements about the other samples have been equally misleading in the depth of hole presumed to be represented by the specimen obtained.

It is quite generally recognized that in well logs not supervised or consistantly sampled by a geologist in attendance at the time of drilling, formations can be indicated only approximately, and minor variations in thickness mean little unless the change in character of rock is so abrupt and decisive that the driller recognizes marked ease or difficulty in his operation at that level. Thus, in passing from Jordan sandstone into the St. Lawrence formation, the driller cannot differentiate between a hard, sandy rock that may constitute the base of one formation, and the slightly dolomitic, sandy rock of the same color, hardness, and texture that may belong to the formation below. This is especially true when there are no visible fossils

[5] N. H. Winchell, *19th Ann. Rept. Geol. Nat. Hist. Surv. Minn.* (1890), pp. 140–43.

in the cuttings, as is generally the case in the sandy beds of the St. Croix series. However, the driller can recognize color change; and he begins the St. Lawrence log where the light-colored sandy phase changes to the dark, argillaceous, dolomitic shale that comes up in the bailer as a gray-green mud. This is not likely to occur until the drill penetrates the trilobite bed (Lodi shale) of the St. Lawrence formation. This may be 30 feet or more below the contact, and the Jordan sandstone is then shown too thick by that amount. The recorded variable thickness of the Jordan in adjacent wells of the Minneapolis–St. Paul–Stillwater basin may be due chiefly to this error.

The Oneota dolomite crops out along the side of the old valley adjacent to the deep well. In order to determine the elevation of the top of the Jordan sandstone and relate it to the well log, Mr. H. S. Grove, superintendent of the water works, had a 20-foot pit or shaft sunk between the well and the outcrop. A sharp Jordan-Oneota contact was thus uncovered 10 feet below the surface or at an elevation of 770.54 feet A.T. Below that the excavation showed the typical coarse, yellow sandstone of the upper part of the Jordan.

The section described in Table II was exposed in the shaft or pit adjacent to the Stillwater deep well, October 12, 1934. The level of the door sill at the well house is 780.64 feet A.T.

These data check very closely with a tracing on file in the local water department which shows an excavation for the upper portion of the well in material as follows: "earth and broken rock, 9 feet; lime rock, 5 feet; Silurian sandrock, 8 feet. From this point a 12-inch pipe extends downward." It is probable, therefore, that the well log as given by Meeds started 8 feet below the Jordan-Oneota contact, or at 762 feet A.T.

At Stillwater the St. Lawrence–Jordan contact is not very clearly marked. About 30 feet of the rock within which this contact must lie is a fine-grained, laminated, gray to buff sandstone passing gradually into slightly dolomitic layers which are on the border line between sandstone and shale. Most of these beds show fucoids or wormlike trails and tubes similar to those so commonly found in the typical St. Lawrence. A conglomerate also occurs within this zone, but conglomerates seldom have any great stratigraphic significance in the St. Croixian series, and this one has probably received too

much attention. The Jordan sandstone at Stillwater is commonly regarded as thin; but if the interval between the two easily recognized horizons represented by the tribolite bed (Lodi shale) of the St. Lawrence and the clearly marked Jordan-Oneota contact be considered, the results seem quite satisfactory. Thus at Boom Hollow, 3 miles north of Stillwater, this interval is 112 feet. In the Stillwater deep well it is 111 feet between the Jordan-Oneota contact and the horizon at which the sample of the St. Lawrence trilobite bed (Lodi shale) was collected. Since the thickness of this latter is usually about 3 feet, and the sample may have been taken anywhere within

TABLE II

	Thickness in Feet
ONEOTA DOLOMITE	
8. Dolomite, massive, gray to brown, partly outcropping but well exposed by the excavation	4.1
7. Dolomite, massive, gray to brown or buff, lower part slightly sandy but showing a sharp contact with the underlying formation. Jordan-Oneota contact at 770.54 feet A.T.	6.0
JORDAN SANDSTONE	
6. Sandstone, very hard, coarse, brown; the sand grains partly reconstructed	2.9
5. Sandstone, hard, brown to white, coarse and with sand grains reconstructed to quartz crystals	0.8
4. Sandstone, brown, fairly well cemented	2.0
3. Sandstone, yellow to brown, poorly cemented	1.0
2. Sandstone, yellow to white, very poorly cemented	1.0
1. Sandstone, loose, white	1.2

the bed, the interval is essentially identical at Boom Hollow and at Stillwater. In the Boom Hollow section the trilobite bed (Lodi shale) lies 37 feet below the St. Lawrence–Jordan contact. If this interval be considered the same in the Stillwater deep well, the thickness of the Jordan sandstone is 74 feet at the well, or only slightly less than its average thickness at St. Paul. At any rate, these two horizons (Jordan-Oneota contact and Lodi shale) are now definitely located in the Stillwater deep well, and a more accurate correlation of the cuttings is possible.

The pit dug adjacent to this well and the section thus exposed

TABLE III

Correlation of the Stillwater Deep Well

Original elevation of drilled well was probably 762 feet.

Feet	Data from Pit Excavated in 1934	Formation
10.1	Dolomite	Oneota base, elev. 770 ft.
8.9	Sandstone	
Sample Taken At	Well Log	Jordan 74 ft.
18	Yellow sand	
	Interval 85 ft. — 48 ft. assigned to Jordan	Estimated contact elev. 696 ft.
	Interval 85 ft. — 37 ft. assigned to St. Lawrence	
103	Calcareous silt, Lodi shale	St. Lawrence 205 ft.
142	Gray sand, some glauconite	
162	White sand, some glauconite	
203	Fine sand with glauconite	
215	White sand with scattered glauconite	Estimated contact elev. 491 ft.
271	Sandy, gray shale	
302	White sand, fossil fragments, etc.	Franconia 78 ft.
312	Medium to coarse white sand, some glauconite	
322	Same	Estimated contact elev. 413 ft.
349	Gray to white sand, fossil fragments	
380	Fine, white sand and sandy shale, glauconite	Dresbach 191 ft.
450	Gray to white sand, glauconite and dolomite	
460	White sand, some glauconite	Estimated contact elev. 222 ft.
540	Pink to buff sandy shale	
630	Coarse gray to white sand	Hinckley 177 ft.
680	Coarse white sand	
688	Coarse yellow to pink white sand	
701	Dark-red sandy shale	
706	Coarse red, brown, white sand	Estimated contact elev. 45 ft.

TABLE III—*Continued*

Sample Taken At	Well Log	Formation
717	Sandy, dark-red shale	
796	Dark-red to brown sand	
892	Same	
923	Dark-red to brown arkose	
952	Dark-red to brown arkose sand	Red Clastics 2,458 ft.
2,250	Coarse, red to brown arkose	
2,570	Same	
2,900	Arkosic sandstone	
2,946	Arkose	
2,950	Dark-red to brown arkose	
3,100	Brownish quartz sand with feldspar	Estimated contact elev. −2,413 ft.
3,175	Dark-brown diabasic rock, diabase flow	
3,230	Dark-brown rock with vein minerals	
3,245	Dark-brown igneous rock	
3,263	Same	
3,271	Same	
3,275	Dark-brown basic igneous rock with serpentine	
3,300	Diabase, copper reported	Keweenawan flows 325 ft.
3,305	Diabase	
3,310	Diabase, fine grained	
3,401	Same	
3,440	Somewhat altered diabase	
3,500	Fine-grained gabbro—Winchell	Estimated well base, −2,738 ft.

show the Jordan-Oneota contact at an elevation comparable to that of the outcrops in other parts of Stillwater. The restudy of the samples from the well shows normal sediments for the various Cambrian formations penetrated. Even fragments of fossils may be found among the cuttings.

The restudy also showed conclusively that the calcareous and dolomitic silt, encountered at 103 feet and represented by sample No. 2, is not Oneota dolomite, as supposed by Hall, Meinzer, and Fuller,[6] but the trilobite bed (Lodi shale) of the St. Lawrence formation. The well log, therefore, shows no evidence of faulting and is given the interpretation shown in Table III.

[6] *Op. cit.*, p. 366.

PITS IN COASTAL PAHOEHOE LAVAS CONTROLLED BY GAS BUBBLES

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ABSTRACT

Certain small pits in pahoehoe flows along the shore are described and attributed to the enlargement by etching and perhaps abrasion of gas bubbles.

The authors in 1930 and 1931 co-operated in a field study of wave-cut features on the Island of Hawaii, of which the present paper is a by-product. There were noted at a number of places both loose

FIG. 1.—Pitted pahoehoe block built into a wall at Kona Inn, Kailua, Hawaii

blocks of pahoehoe lava and pahoehoe ledges in situ with subparallel, curving rows of small pits. The pits are nearly circular, 1 to 2 inches in diameter and 1 to 1½ inches deep. They are spaced 2 to 4 inches apart in the rows, and the rows are spaced at like intervals. Such a pitted block, which has been built into a wall at Kona Inn, Kailua, is illustrated in Figure 1. A loose block, collected half a mile south of Kailua is illustrated in Figure 2.

The hypothesis that they were "checkerboards," or *papakonane*, such as the primitive Hawaiian made (Fig. 3), was abandoned be-

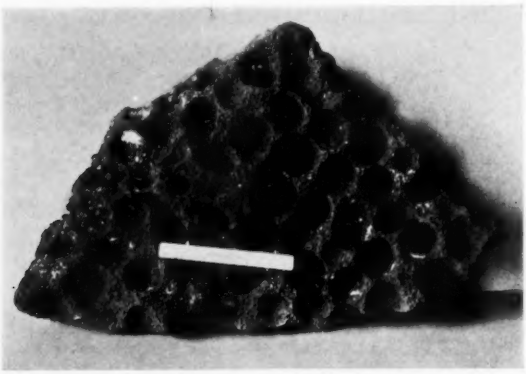

FIG. 2.—Pitted pahoehoe block collected one-half mile south of Kailua, Hawaii

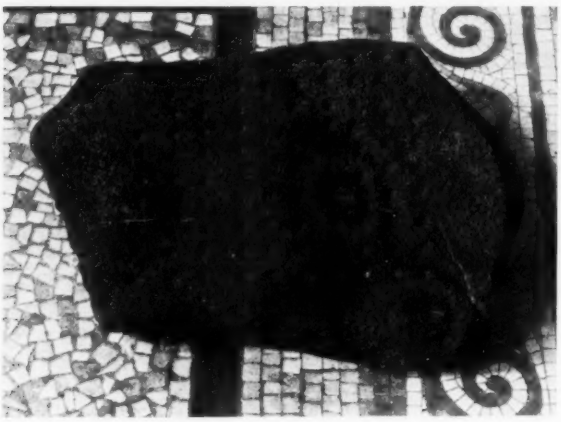

FIG. 3.—Ancient Hawaiian checkerboard or *papakonane* in the Bishop Museum, Honolulu.

cause the patterns in the various examples differed from one another too much, and because the holes were too deep for convenience in play. Another hypothesis, namely, that the pits are the work of

sea urchins, was necessarily abandoned when pitted ledges were found too far inland. Thus we were left without any explanatory hypothesis until we happened upon several outcrops which between them gave us the chief stages in a genetic series or cycle of development.

Pahoehoe flows form eventually a brittle, glassy surface, but during cooling, the surface lava, destined to form the skin, passes from great fluidity through stages of increasing viscosity before becoming a vitreous solid. When stiffly fluid, the skin is dragged onward by

FIG. 4.—Elephant-hide pahoehoe lava, slightly abraded, Hookena, Hawaii

the still-advancing, more fluid interior, and it is thereby wrinkled and crumpled in many fantastic ways. One product is "elephant hide" or "festoon" pahoehoe, which is characterized by being covered by subparallel, curving wrinkles or ropes. Those in Figure 4 are 2 to 8 inches from crest to crest. The decrease in volume on cooling produces tension, to which the pahoehoe yields by jointing both parallel to and at right angles to the long axes of the wrinkles. The transverse joints are 1 to 5 inches apart. The faces of the joint blocks toward the camera in Figure 5 are the two aspects of a single transverse joint along which the two blocks of rock were separated. The faces on the right and left of each block are longitudinal joints. The longitudinal joints are inconspicuous on bed rock outcrops for they are down between the wrinkles.

The up-arched, partly hardened skin of the wrinkles makes miniature anticlines under which are trapped bubbles of gas released from the lava as it cooled. (It is odd that the anticlinal theory of oil

FIG. 5.—Two mated joint-blocks, with a bubble halved, Hookena, Hawaii

FIG. 6.—Partly unroofed, broad wrinkle of elephant-hide pahoehoe lava, Hookena, Hawaii.

and gas accumulation should have so close an analogy in a volcanic process!) In Figure 6 we see a partly unroofed wrinkle of unusually great width. The pair of blocks shown in Figure 5 were collected from the same locality as that shown in Figure 6, but not from the

same field of view. However, the joint blocks to the left of this stripped area were found to contain similar bubbles. Such bubbles are the first stage in the cycle leading finally to the deeply pitted surface.

The pits of the blocks in Figures 1 and 2 have been modified and enlarged, after first being exposed by the removal of the shell of the wrinkles beneath which the gas bubbles were trapped. The enlargement seems to have been by solution and etching in the manner described by Scherber[1] for numerous pits in sandstones near Livorno, Italy. It is evident that the Hawaiian variety of pits originated by the exposure of the bubbles when the top, brittle, glassy shell of the pahoehoe wrinkles had been removed. Once such pits have been exposed, they tend to catch and hold water, which attacks and dissolves the rock of the sides of the pits. The effect is undoubtedly augmented by the salts in sea water. The waves of subsequent storms may break over the ledge or at least throw much spray over it. Either will serve to rinse out the pits and enlarge as well as to refill them with another supply of water to resume the dissolving and etching attack. Perhaps sand is swirled around in the pits at times to enlarge them by a pothole variety of abrasion. Many of the pits contain sand, at all events.

The processes combine to enlarge all the pits at the expense of the intervening rock partitions. Thus the partitions between pits are narrowed until they disappear. Several stages in the enlargement and destruction of the pits may be seen in the accompanying illustrations, especially in Figure 6.

In brief, the perplexing pits appear to be derived from gas bubbles which (1) were originally trapped under the wrinkles of elephant-hide pahoehoe lava; (2) were exposed by stripping of the shell of the wrinkles; and (3) were more or less enlarged by the etching and rinsing action of salt spray, and by sand abrasion.

[1] Rudolf Scherber, "Erosionswirkungen an der Toskanischen Felsküste," *Natur und Museum*, Band 62, Heft 7 (July, 1927), pp. 231–34.

SOME CENTRAL TEXAS WELLS THAT FILLED WITH WATER

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ABSTRACT

In central Texas on the east flank of the West Texas Permian Basin the drainage is easterly, and the Carboniferous and Permian beds dip westward. Waters from the lower part of the Permian Wichita group rise definitely higher than the local water table in three wells among those studied. Thus, these are not ordinary water wells. Artesian hydrostatic pressure is not the pressure that causes these waters to rise, because the wells are on ground higher than the lowest points of outcrop of the aquifers. The waters are not "free," because their pressures are less than would be those of such waters. The waters are thought to rise higher than the local water table in these wells because of a ground-water hydrostatic pressure generated by the downward passage of water from the surface through the rocks, many of which, though called "impervious," are actually slowly permeable.

INTRODUCTION

In central Texas on the east flank of the West Texas Permian Basin the drainage is easterly, and the Carboniferous and Permian beds dip gently westward (Fig. 1). Here many buttes, mesas, and peninsula-like areas stand relatively high. These highlands are capped by remnants of Lower Cretaceous (Comanchean) formations which formerly covered the entire area, lying on the Gulfward-sloping pre-Cretaceous peneplain. Colorado River is the principal stream.

Many wells have been drilled in the area to test for oil, and most of them have encountered waters; but because of lack of interest, water data have been kept in a very desultory manner. Oddly enough, the driller's term, "hole full of water," merely means that water comes into the well so rapidly that it cannot be carried while drilling. Thus the term expresses only a crude measure of permeability. The height to which a water rises in a well usually is not kept. A water reported as less than "3 bailers an hour" may rise to the surface; whereas a so-called "hole full of water" may not rise to within 500 feet of the surface. Water pressures are usually not gauged even when water flows out at the surface. But if a water fills a well nearly to, or to, the surface without jetting, it must be under a pressure about equal to that exerted by a column of water as

high as the aquifer is deep. However, this measure of pressure is very crude, because many waters have not volume enough to jet even when the well is cased, preventing escape into the zone of cavities and mantle rock. Undoubtedly, many waters, rising in wells that are not cased, flow off into the zone of solution cavities

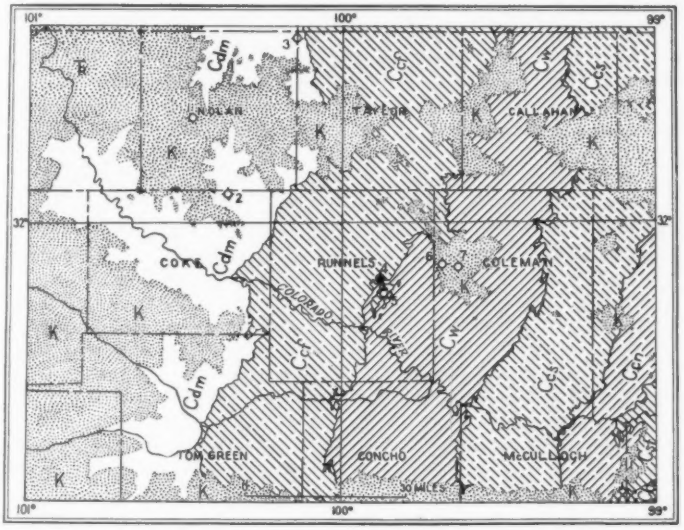

FIG. 1.—Geologic map of an area in central Texas showing the wells Nos. 1–7, used in the section (Fig. 2). Stippled areas are those of Mesozoic and younger rocks, mostly Lower Cretaceous (Comanchean). Named from oldest to youngest, the Carboniferous and Permian rocks are: *Cb*, Bend group (Mississippian and Pennsylvanian); *Cst*, Strawn formation (Pennsylvanian); *Ccn*, Canyon group (Pennsylvanian); *Ccs*, Cisco group (Pennsylvanian and Permian); *Cw*, Wichita group (Permian); *Ccf*, Clear Fork formation (Permian); *Cdm*, Double Mountain group (Permian).

above the water table, so that they do not rise to the surface, though they may be under pressures sufficient to raise them to that height.[1]

STRUCTURE SECTION

The accompanying structure section (Fig. 2) shows the wells discussed and the subsurface stratigraphy obtained from a study of

[1] I am indebted to Professor R. T. Chamberlin of the University of Chicago for many helpful suggestions and criticisms.

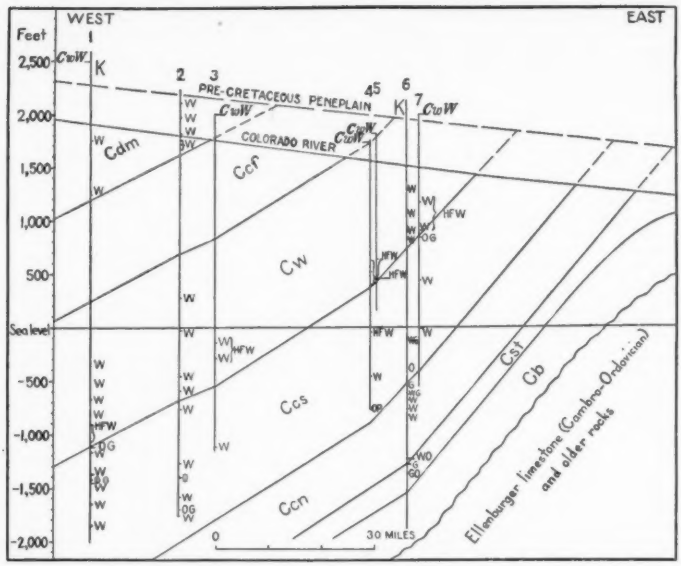

FIG. 2.—Structure section along Colorado River from the north line of Coke County to the east line of the map (Fig. 1), showing the stratigraphy and water data of the wells shown on the map. Well symbols are: *CwW*, height to which water from the lower part of the Wichita is known to have risen; *HFW*, water that filled the well; *W*, water; *O*, oil showing; *OP*, oil production; *G*, gas showing.

As numbered on the map, the wells are: *No. 1*, Wichita Nolan Oil Co. No. 1 Kuteman (NE. cor. SE. ¼ sec. 79, blk. X, T. & P. R.R. Co. surv., Nolan County); *No. 2*, Mid-Kansas O. & G. Co. No. 1 C. J. Henry (SW. ¼ sec. 271, blk. 1A, H. & T. C. R.R. Co. surv., Coke County); *No. 3*, Root Drg. Co. No. 1 Martin (SW. ¼ sec. 30, blk. 19, T. & P. R.R. Co. surv., Nolan County); *No. 4*, Golden Petr. Co. No. 1 R. M. McMillan (SW. ¼ Norvell Travis surv. No. 533, Runnels County); *No. 5*, R. B. Summers No. 1 J. W. Reese (center Day L. & C. Co. surv. No. 1, Runnels County); *No. 6*, Kingwood Oil Co. No. 2 J. A. McCord (NW. ¼ B. B. B. & C. R.R. Co. surv. No. 41, Coleman County); *No. 7*, McIntyre Oil Co. No. 1 D. W. Grounds (SW. ¼ sec. 5, blk. 2, T. & N. O. R.R. Co. surv., Coleman County).

The Carboniferous and younger rocks are: *Cb*, Bend group (Mississippian and Pennsylvanian) of limestone and shale; *Cst*, Strawn formation (Pennsylvanian) of shale, limestone, and sandstone; *Ccn*, Canyon group (Pennsylvanian) of limestone, shale, and some sandstone; *Ccs*, Cisco group (Pennsylvanian and Permian) of shale, limestone, sandstone, and red beds; *Cw*, Wichita group (Permian) of shale, limestone, and anhydrite; *Ccf*, Clear Fork formation (Permian) of red beds, shale, limestone, and anhydrite; *Cdm*, Double Mountain group (Permian) of red beds and sandstone (and salt beds in the Permian Basin); *K*, Lower Cretaceous (Comanchean) of limestone, sandstone, and shale.

well samples and records. The wells are placed in the section so that their elevations and stratigraphic positions at the surface are shown graphically. Water data and heights to which waters from the lower part of the Wichita group are known to have risen are shown. The wells were selected for their conspicuous locations high above Colorado River, and are only a few of the many that have been drilled.

HEIGHTS TO WHICH WATERS RISE

Wells drilled into the lower part of the Wichita group usually en-encounter salty waters there. In some wells these waters are reported as a few bailers an hour; but in others, as "holes full of water." The rocks of this horizon are limestone and shale; and their permeability, if this property can be estimated from the reports of the waters, is somewhat less than that of the usual water-bearing sandstone.

Salty waters have flowed out at the surface from some wells in Runnels and Concho counties from a horizon in the lower part of the upper one-third of the Cisco group.

Well No. 1.—Salty waters were encountered in Well No. 1 in the lower part of the Wichita. After an attempt to case off these waters, drilling proceeded until a showing of oil and gas was encountered near the top of the Cisco, when the well was shut down for more than a year, with water standing within about 100 feet of the surface.[2] Thus these waters rose and remained at a height of about 2,500 feet above sea level, and about 1,019 feet higher than the outcrop of the horizon in the Colorado River valley.

Well No. 2.—All the Clear Fork and younger rocks in Well No. 2 were cased off—very far below the zone of solution cavities—before drilling proceeded into the lower part of the Wichita. "Holes full of water" were reported from this horizon, signifying that the waters came into the well rapidly. Yet water from no horizon filled the well, though water at 475–490 feet (in the lower part of the Double Mountain group) "filled up to possibly 300 feet from the top but did not fill to the surface."[3] Thus the waters from the lower part of the Wichita were under lower pressures than were those in Well No. 1,

[2] George Eatwell, Maryneal, Texas, oral communication, September 17, 1934.

[3] A. L. Henderson, Iraan, Texas, personal communication, August 9, 1934.

which rose about 260 feet higher than the surface at Well No. 2 and 550 feet higher than the height reached by any water in Well No. 2. If these lower Wichita waters were under pressures of the type commonly known as "artesian," they should have filled Well No. 2 to the surface, and might be expected to have done some jetting.

Well No. 3.—Waters from the lower part of the Wichita in Well No. 3 flowed out at the surface without jetting.[4] These waters rose about 525 feet higher than the outcrop of the horizon in the Colorado River valley.

Well No. 4.—The lower Wichita waters filled Well No. 4 to within about 20 feet of the surface,[5] where, as the well was not cased, they doubtless flowed out through joints and cavities in the Lueders limestone (the top member of the Wichita) into a creek a few hundred feet south of the well. These waters rose about 250 feet higher than the outcrop of the horizon in the valley of Colorado River.

Salty water from near the bottom of the upper one-third of the Cisco group flowed out at the surface from Well No. 4 without jetting. The well was cased to below the top of the Cisco, so that this water could rise in the pipe through the zone of cavities. This water rose about 350 feet above the outcrop of its horizon in the Colorado River valley.

Well No. 5.—Well No. 5 is 3 miles south of Well No. 4, and its surface elevation is 63 feet higher than that of Well No. 4. Yet the lower Wichita waters filled Well No. 5 and still flow out at the surface. These waters,[6] aggregating about 6 bailers an hour, were carried while drilling to about 250 feet below the lowest aquifer, when drilling was discontinued at midnight, May 28, 1928. The waters had filled the well $3\frac{1}{2}$ days later, and within the week had filled 7 feet of the 10-foot cellar, at which level the waters evidently seeped into the mantle rock. The waters filled the cellar about $3\frac{1}{2}$ years later in the autumn of 1931, and since then have flowed out at the surface. These waters rise about 335 feet higher than the outcrop of their horizon in the valley of Colorado River.

[4] William Morris, Ballinger, Texas, oral communication, September 8, 1934.

[5] Harry Cannon, Ballinger, Texas, oral communication, September 21, 1934.

[6] J. W. Reese, Ballinger, Texas, oral communication, February 16, 1935.

Well No. 6.—Six wells have been drilled on the Cretaceous highland in western Coleman County; and only one of these, Well No. 7, filled to the surface with water.[7] All five wells that were not filled were cased below the level of Colorado River—below the zone of solution cavities—before drilling proceeded into some of the lower Wichita aquifers. Thus, if the waters were under sufficient pressures, they should have risen to the surface without loss. Well No. 6 was not filled to the surface with water, though the three lowest waters in the lower part of the Wichita were reported as "holes full of water," indicating that the permeability of the aquifers was high.

Well No. 7—Lower Wichita waters flowed out at the surface from Well No. 7. These waters rose about 500 feet higher than the outcrop of their horizon in the Colorado River valley. This well has the lowest surface elevation of all the wells on the Cretaceous highland in western Coleman County.

THE PRESSURE THAT CAUSES THE WATERS TO RISE

The following quotation gives the usual conception of ordinary water wells:

> An ordinary well is an opening dug or drilled into the ground to a depth sufficient to penetrate the saturated zone. The water percolates into the opening from the saturated material around it but *does not rise in the well above the level of the water table.*[8]

Thus, of the seven wells described here, at least three (Wells Nos. 3, 5, and 7) definitely are not ordinary, for waters from them flowed out at the surface, and none of the seven wells is on marshy ground where the water table reaches the surface.

"When surface water enters and saturates a pervious, inclined layer confined between two impervious layers the weight of the water in the aquifer generates hydrostatic pressure."[9] Under these conditions, commonly called "artesian," water may rise above the

[7] Will Galloway, Coleman, Texas, oral communication, September 8, 1934; Morris, *loc. cit.*

[8] L. V. Pirsson, *A Textbook of Geology*, Part I, *Physical Geology* (3d ed.; New York, 1929), p. 135. The italics are mine.

[9] *Ibid.*

water table in a well penetrating the aquifer. But as the Carboniferous and Permian beds of this area dip westward and the drainage basin slopes eastward, the waters in these rocks are not under artesian hydrostatic pressures sufficient to fill wells unless they come from the other side of the basin. Pennsylvanian and Permian strata,[10] unlike those of central Texas, crop out on the other side of the basin in trans-Pecos Texas and southeastern New Mexico about 125 miles west of the area considered. Though these outcrops are high enough to afford the requisite hydrostatic pressures, if waters could get through from them—through the probably block-faulted buried mountains in the basin[11]—to the area considered, these waters would pass on eastward and flow out at the lowest outcrops of the aquifers. Under artesian conditions, some loss of head because of friction would probably occur from west to east across the area. But the lower Wichita waters in Well No. 1 rose about 1,019 feet higher than the outcrop of the aquifer in the valley of Colorado River and 550 feet higher than the height reached by any water in Well No. 2, though Well No. 1 is about 65 miles west of the outcrop of the aquifer and Well No. 2 is only about 10 miles less distant west from the outcrop. Thus the waters in these two wells should have more nearly equal heads, if these heads were artesian. Nor are these inequalities of head due to depletion, for these waters are not used, and most wells are plugged when abandoned, so that intake would readily keep pace with any slight depletion. This anomaly of head must be due to some more local cause than loss of artesian head because of friction, if such loss of head could be as great as 1,000 feet in 65 miles. Evidently, artesian pressure is not the cause of the rise of these waters.

Though the limestones of the region are jointed at their outcrops, probably fissures and faults have not afforded passages for the flow of water from the surface to the lower part of the Wichita, for much shale is in the section above this horizon, and most of the few faults in the area are probably mere landslips in bluffs.

[10] L. D. Cartwright, Jr., "Transverse Section of Permian Basin, West Texas and Southeast New Mexico," *Amer. Assoc. Petrol. Geol. Bull. 14* (1930), pp. 969–81.

[11] H. P. Bybee, "Some Major Structural Features of West Texas," *Univ. Texas Bull. 3101* (1931), pp. 19–26.

If these waters were "free," as postulated by Snider for some waters from the Goose Creek field,[12] occupying space in addition to the pores in the rocks in "thin layers, or beds, or pimple-like bodies" between strata, they would be under far greater pressures than those observed, and probably would spout from the wells, for such waters would support much of the weight of the rock column and could certainly rush into wells.

The waters under consideration differ from those in ordinary wells in rising above the water table. But what pressures cause these waters to rise so much higher than the lowest outcrops of their aquifers? For these aquifers are separated from the zone of ground water near the surface by hundreds of feet of rocks apparently barren of water and usually considered as impervious. Gardner[13] and Versluys[14] have pointed out that subsurface fluids and gases are under pressures about equal to the pressure exerted by a column of water as high as the containing rock is deep at the point considered. The described waters appear to be under such pressures; and if all the rocks, including those ordinarily called "impervious," beneath the water table to the aquifers are actually saturated, an explanation of these observed pressures is readily apparent. Evidently, ground water from other places where it is higher than the top of the well seeps through the rocks, connects with the water in the aquifer, and produces a ground-water hydrostatic pressure sufficient to cause water from the aquifer to rise in a well higher than the local water table.

If ground-water hydrostatic pressure may cause water from an aquifer to rise in a well higher than the local water table, many so-called "impervious" rocks must be slowly permeable; but apparently water comes into wells from such rocks too slowly to be noticed. Such downward passage of water from the surface through

[12] L. C. Snider, "A Suggested Explanation for the Surface Subsidence in the Goose Creek Oil and Gas Field, Texas," *Amer. Assoc. Petrol. Geol. Bull. 11* (1927), p. 736.

[13] J. H. Gardner, "The Mid-Continent Oil Fields," *Geol. Soc. Amer. Bull. 28* (1917), pp. 700–702.

[14] J. Versluys, "Can Absence of Edge-Water Encroachment in Certain Oil Fields Be Ascribed to Capillarity?" *Amer. Assoc. Petrol. Geol. Bull. 15* (1931), p. 190.

so-called "impervious" rocks that are actually slowly permeable may explain the high salinities of some oil-field waters—as, for example, water more than seven times as saline as sea water in the Gose horizon (lower Cisco, stratigraphically lower than salt beds of the Permian Basin) south of Electra, Texas[15]—and may explain how sulphate-reducing bacteria[16] have got into some subsurface waters.

[15] V. E. Barnes, "Oil-Field Waters of North-Central Texas," *Amer. Assoc. Petrol. Geol. Bull. 16* (1932), pp. 409–11.

[16] E. S. Bastin, "The Problem of the Natural Reduction of Sulphates," *Amer. Assoc. Petrol. Geol. Bull. 10* (1926), pp. 1270–99, 1298.

THE FOUNDATIONS OF ATOLLS: A DISCUSSION

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ABSTRACT

The problem of the origin of barrier reefs and atolls is biological as well as geological. By failing to determine the organic composition and the age of elevated limestones, some workers have given much undeserved support to the theory of subsidence. Unconformable contacts between elevated limestones and older volcanics on tropical islands have little bearing on the subsidence theory unless the limestones are coralliferous. Recent studies show that many elevated coral reefs have a foundation of non-coralliferous limestone, and in some cases this limestone is geologically considerably older.

The basin-shaped limestone islands in Fiji which certain writers have interpreted as elevated atolls are not usually to be so considered. Under proper conditions the basins are formed by subaërial solution regardless of the structure, age, or organic composition of the limestone. Even tiny remnants of so-called much dissected, elevated atolls show individually well-developed basin shapes.

In a recent number of this journal[1] the late Professor W. M. Davis discussed J. Stanley Gardiner's book, *Coral Reefs and Atolls*.[2] He praised very highly the chapters which deal with reef-building organisms, and criticized very severely the chapter entitled "The Foundations of Atolls," which is devoted to the problem of the origin of coral reefs. Davis also criticized the publications of nine other British biologists who have studied the origin of coral reefs. He charged them with a neglect of the geological factors involved in the problem. It appears to us that, though much of his criticism is justified, Davis and some other geologists are at least as guilty of befogging the coral-reef problem as are the biologists, for they have, in their turn, ignored important biological considerations. By a brief discussion of the problem we shall try to show that it is biological as well as geological, and shall support this contention with a series of concrete examples. These examples, particularly those in eastern Fiji, which we have recently studied in the field, furnish new information on the foundations of atolls.

The first section of Davis' discussion is entitled: "The Origin of Coral Reefs Is a Geological Problem." He stated that as coral reefs

[1] W. M. Davis, "Gardiner on Coral Reefs and Atolls," *Jour. Geol.*, Vol. XLII (1934) pp. 200–217.

[2] J. Stanley Gardiner, *Coral Reefs and Atolls* (Macmillan Co., 1931).

are a product of lime-secreting organisms they have been studied by a number of biologists, especially British biologists. "But," he continued, "though the study of living reef-builders is evidently a biological problem, the discovery of the conditions and processes of the past under which the massive reef structures have been formed is as evidently a geological problem." Thus he separated the study of the organisms which compose the reefs from the study of the past history of the reefs, considering these two distinct problems—the former the field of the biologist and the latter the field of the geologist. However, a few lines below he said: "The nature of the invisible past can be learned only by making back-reaching inferences from the observable present." These statements do not seem entirely consistent. Davis probably meant that the geologist should acquaint himself thoroughly with both the geologic and biologic conditions of the present as obtained from his own observations and from the work of the biologist before making his "back-reaching inferences" which result in a theory for the origin of coral reefs. The biologist should consider primarily the structure, ecology, and distribution of the organisms which live on and around the reefs and thus determine what part they play in reef formation. He should then make a close acquaintance with geological methods before proclaiming any theory of reef origin.

If this is what Davis meant, we agree with him and believe that if such practices had been closely adhered to in the past the solution of the problem would be much closer than it is today. However, this makes the problem of the origin of coral reefs, not one for the geologist alone, but one for the biologist as well. It becomes a joint study in which the work of both is indispensable.

GEOLOGICAL CONSIDERATIONS

In criticizing the biologists, Davis claimed that their neglect of the geological factors was due either to ignorance or to indifference to these factors. For example, he stated[3] that Murray did not take into consideration the embayed shore lines of the central volcanic islands and, when once asked about them, retorted: "What have they to do with it!" According to Davis, this same attitude has

[3] *Op. cit.*, p. 203.

featured the writings of the majority of biologists who have worked on this problem. His chief criticism was aimed at the recent publication by Gardiner, to which he devoted the larger part of the paper.

BIOLOGICAL CONSIDERATIONS

Now, if it is true that biologists have at times failed to take into account fundamental principles of geology in their attempts to solve the coral-reef problem, it is equally true that many geologists have woefully failed to consider biological factors which are just as important. Specifically, when studying elevated limestones which may possibly have been barrier reefs or atolls, they have failed to determine the organic composition of the rocks, and from this to deduce the conditions under which they were formed. In some instances a limestone in which a fragment of a coral has been found has, without further examination, been dubbed a "coral-reef limestone." Various theories of reef origin have been given support by this type of inadequate observation, and considerable confusion has resulted because many of the so-called "coral-reef limestones" have, on closer examination, proved to be of entirely different origin. Cases of this sort are given later in the discussion of several key islands.

The failure of many geologists to determine the structure and organic composition of elevated limestones has also caused confusion when they have attempted to describe and explain the contacts which such limestones make with the underlying volcanic rocks.

Davis has pointed out many examples of islands where the limestone lies unconformably on volcanic rocks, and has based a large part of his evidence for the subsidence theory on the study of such islands. The chapter in Gardiner's book on "The Foundations of Atolls" received particular attention in Davis' review. Gardiner was taken severely to task for not describing the volcanic rocks beneath the limestones and the nature of the contacts. Said Davis: "Not a word is said about the foundations beneath the limestones."[4] Thus Davis apparently believed that the foundations of atolls and barrier reefs are synonymous with the foundations of the limestones. Nothing could be farther from the truth. Many elevated coral reefs

[4] *Ibid.*, p. 210.

have a foundation of other types of limestone, and in some cases these limestones are geologically considerably older. In other words, the finding of unconformable contacts between limestones and underlying volcanic or other non-calcareous rocks need not necessarily be a point in favor of the Darwinian theory of subsidence.

First of all, let us consider the types of limestone. According to Davis, the undermass of an up-growing reef on a slowly subsiding island consists in part of "lagoon limestones" lying unconformably upon the previously emerged and subaërially eroded slope of the island.[5] These lagoon limestones may be expected to show bedding, for they will include a considerable amount of detrital material and large numbers of small shells, such as those of foraminifera. We contend, however, that they should not be entirely free of corals. Sporadic growths of corals—particularly large massive colonies—occur in all lagoons, and much coral débris is received from the barrier reef. Also, we have observed that a fringing platform of some sort is usually developed on islands surrounded by barrier reefs. At the seaward edge of this platform corals are very abundant; and living colonies of hardy types, such as *Porites*, are scattered over its surface. It is inconceivable that thick deposits of non-coralliferous limestones could accumulate in a lagoon. Therefore, such limestones cannot be used to support the subsidence theory even if they do overlie volcanic rocks unconformably.

Secondly, the limestones which overlie the volcanic foundation unconformably may be appreciably older than the reef limestone above. If such a difference in age can be established, the presence of an unconformity below the older limestone has no bearing whatever on the subsidence theory. The structure, composition, and age of the limestones above the volcanic rocks, therefore, are most important matters and must be determined before the character of the contact can be used to support any theory of reef origin. Examples of the neglect of this biologic factor are drawn from the following islands.

Eua in the Tongan group.—Eua, near the southern end of the Tongan group, is an elongate island which rises to a height of about 1,000 feet and is capped by limestone. Davis did not visit this island

[5] *Ibid.*, p. 211.

but, presumably on the basis of physiography, described it as an elevated atoll. It, however, is not shaped like an atoll; so he postulated down-faulting of the eastern half to account for its present shape.

In 1891, John Murray made an examination of the limestones of Eua collected by Lister. He found that in the majority of cases the limestones were developed by organisms other than corals. From the scarcity of examples of the larger corals he concluded that "it is more likely that they [the limestones] were laid down in depths of from 30 to 100 fathoms, and that they formed the *base* of true coral-reefs."[6]

Furthermore, Lister stated: "The limestones from the higher part of the island present from the most part a compact structure. Some of them are crowded with foraminifera, but large masses of coral appear to be absent."[7] Here is good biological information which throws considerable light on the history of the island. Davis, however, ignored it and made the island an uplifted coral atoll. He referred to it as "the loftiest elevated reef in the open Pacific."[8] In 1926, Hoffmeister spent two months on Eua and found, exactly as Lister and Murray had stated, that the limestones of the upper part of the island were composed almost entirely of foraminifera remains and therefore could not possibly be considered as a part of a coral atoll. Furthermore, the interesting discovery was made that these limestones are Eocene in age. Inasmuch as the coral limestones which overlie the Eocene rocks are Pliocene, this is further evidence against Davis' interpretation. When Hoffmeister's report[9] appeared in 1932, Professor Davis very magnanimously wrote, in a personal letter, "I am greatly interested in the geology of the island as you describe it. My supposed facts were mostly wrong. . . . . It shows how risky it is to extend incomplete reports into new interpretations." However, his recent paper in the February–March *Journal*

[6] J. J. Lister, "Notes on the Geology of the Tonga Islands," *Quart. Jour. Geol. Soc. London*, Vol. XLVII (1891), p. 604. The italics are ours.

[7] *Ibid.*, p. 604.

[8] *The Coral Reef Problem*, "Amer. Geog. Soc. Special Publications," No. 9 (1928), p. 416.

[9] J. E. Hoffmeister, "Geology of Eua, Tonga," *Bernice P. Bishop Mus. Bull. 96* (1932).

of Geology shows that he still did not fully appreciate the value of the biological factors involved in the coral-reef problem.

Mangaia in the Cook group.—The island of Mangaia has been cited again and again by Davis as one of the very best examples of an elevated barrier reef. It is one of his chief witnesses testifying to the validity of the subsidence theory. Mangaia was well described by Marshall.[10] It possesses a central volcanic cone which is surrounded by a lower limestone mass, or *makatea*, from which it is separated by a valley or moat. The *makatea* is supposed to represent an elevated barrier reef; and the moat, the former lagoon. Chubb[11] suggested that erosion might have played an important part in the formation of the moat, or "Taro flats," as they were called by Marshall. Hoffmeister[12] agreed with Chubb and stated that the *makatea* might very well be an elevated *fringing* reef which, after elevation, had taken the shape of a barrier. The waters from the volcanic slopes of the central part of the island, after reaching the limestone of the reef, continue seaward by way of the limestone-volcanic contact. In this way the moat could have been formed by solution, and gradually widened as the process continued. The reasons for this belief are fully discussed in Hoffmeister's original paper. It is sufficient here to refer to only a few. In the first place, Marshall's description of the composition of the *makatea* limestone sounds much more like a fringing reef which has grown out slowly over a talus slope of broken coral-reef material than a barrier reef which has grown up according to Darwin's theory. Under this latter theory, which Marshall supports, the limestone should reveal a great many corals in position of growth surrounded by calcareous algae. Also it should be of massive, non-bedded structure; but, although Marshall refers to the *makatea* as being "bedded in appearance,"[13] he also states: "In general, the limestone forming the Makatea has a dense, compact appearance, in which no structure is

[10] Patrick Marshall, "Geology of Mangaia," *Bernice P. Bishop Mus. Bull. 36* (1927).

[11] L. J. Chubb, "Mangaia and Rurutu—a Comparison between Two Pacific Islands," *Geol. Mag.*, Vol. LXIV (1927), pp. 518–22.

[12] J. E. Hoffmeister, "Erosion of Elevated Fringing Coral Reefs," *ibid.*, Vol. LXVII (1930), pp. 549–54.

[13] *Op. cit.*, p. 43.

discernible in hand specimens. Even corals cannot be distinguished and some of the limestone appears like consolidated sand."[14]

Kuenen discusses Mangaia in his interesting report on the geology of the coral reefs of the Dutch East Indies. He says:

> I agree with Hoffmeister that it seems probable that the reefs were of the fringing type, the lagoon having been formed by subsequent subaërial erosion. According to Marshall the rock on the inner wall of the makatea contains a quantity of coral sand. I very much doubt whether a barrier reef could grow up vertically, enclosing a lagoon without calcareous sediments and yet itself contain a considerable percentage of sand on its inner, vertical surface. Marshall's observations seem to me to show that there must at least have been coral sand in the lagoon, in other words, that the Taro flats are at least partly the result of erosion.[15]

This point is well taken and strengthens the argument against the *makatea* being a barrier reef.

Furthermore, on the whole surface of the limestone Marshall could find only two coral heads. These were so poorly preserved that Vaughan was even doubtful about the generic names he applied to them. Marshall found them at the base of the inner cliff. He stated that they were undoubtedly in position of growth. To determine whether coral heads are or are not in their original positions is a rather difficult task. A large area of well-preserved fossil material must be examined. On the island of Vavau in Tonga there is a vertical cliff 600 feet high composed of coral limestone. Hundreds of coral heads can be seen in this cliff face from top to bottom. Some show their heads in an upright position and others are turned upside down. It was only after considerable study that the conclusion was reached that these coral heads are not in position of growth. The finding of two poorly preserved corals with their heads up does not prove that they are in their original place.

Probably one of the most significant discoveries made by Marshall in connection with the geology of this island was the finding of the foraminifer *Lepidocyclina* as a fossil in the reef limestones, and he therefore dates these as Miocene. This biological discovery was a disturbing one to both Marshall and Davis in view of their belief

[14] *Ibid.*, p. 25.

[15] Ph. H. Kuenen, *Geology of Coral Reefs, The Snellius Expedition*, Vol. V, Part II (1933), p. 75.

that the *makatea* is an elevated barrier reef. Each met the question in a different manner. Marshall reasoned that if the *makatea* has been elevated and exposed to erosion ever since Miocene times erosion must be very slight on coral-reef limestone. This solution recognized the importance of the biologic factor involved but brought him to a conclusion which does not seem tenable. Many observers testify that surface water is very effective as an agent of erosion of elevated reef limestones. Davis reasoned that, since there is very little erosion of the *makatea*, the Miocene determination of the limestone must be wrong. He said:

> Thus a contradiction arises between the paleontological and the physiographic evidence as to the history of the reef; and this contradiction recalls a similar one concerning certain basin deposits in the western United States, known as the Equus beds, which Gilbert pointed out years ago, and regarding which he thought the physiographic evidence was more trustworthy than the paleontological. I am much inclined to follow his example and to accept the physiographic evidence as giving a relatively recent date for the making as well as for the emergence of the Mangaia reef and conversely to mistrust the paleontological evidence which makes the reef of Miocene date.[16]

Thus, the correctness of the dating of the limestone, which should be one of the important clues in the history of the reef, was questioned in order that the physiography might be made to fit a particular theory of reef origin. The Miocene age of the limestone, if correct, as it seems to be, points strongly to its origin as a fringing reef which, in the ample time provided since its elevation, has been greatly eroded so that a depression resembling a lagoon now exists between its outer rim and the volcanic hills of the central part of the island. This explanation takes into account both biologic and physiographic evidence and recognizes, as well, the conditions under which an elevated reef limestone is eroded.

Though Davis was aware of Marshall's description of the composition of the *makatea* limestone, he did not mention its internal structure. He seems to have based his conclusions entirely on the physiography of the island. His only comment relative to structure is:

[16] *The Coral Reef Problem*, p. 407.

It is also noteworthy that the evidence as to the manner of origin of the Mangaia and the Rurutu reefs is not found in their internal structure, of which little is known, but, as in the case of elevated fringing reefs, wholly in the unconformable relation of the reef mass to the foundation mass. Furthermore, this relation is determined for Mangaia not so much by the discovery of direct contacts of reef limestone with the volcanic rocks beneath them as by the general topographic relations exhibited by the visible forms of the two kinds of rocks.[17]

It is true, apparently, that the limestone of the island has been so altered that its composition is not so clear as might be desired; however, sufficient is known to make it seem highly probable that it was never a barrier reef.

Tuvuthá and other islands in Lau (eastern Fiji).—Just as Davis considered Mangaia the best example of an elevated barrier reef, so did he look upon Tuvuthá in eastern Fiji as the best example of a raised atoll. We have recently returned from a field season in eastern Fiji, and during that time three weeks were spent in making a detailed examination of the small island of Tuvuthá. A study of the limestones is now in progress; and, though it is still too early to present a complete history of the island, enough has been accomplish to indicate clearly that the limestone rim enclosing the central basins does *not* represent the rim of a former atoll.

A number of writers have described Tuvuthá or commented upon its geological features; but only five, including ourselves, have actually visited the island. The first of these was Agassiz. He merely "touched" at the island. He did, however, express his belief that the island was not an elevated atoll.[18]

In 1898 Andrews visited Tuvuthá. A section on Plate 3 of his report shows a thin coating of "actual raised coral reef" resting on "rubble and probable rubble of coralline origin." And he stated that much of the lower part is undoubtedly a compact, bedded rock.[19] He did not state that Tuvuthá was an elevated atoll, although his report implies this. David, however, in the Preface to Andrews' report, says definitely:

[17] *Ibid.*, p. 410.

[18] Alexander Agassiz, "The Islands and Coral Reefs of Fiji," *Bull. Harvard Mus. Comp. Zoöl.*, Vol. XXXIII (1899), pp. 13, 75.

[19] E. C. Andrews, "Notes on the Limestones and General Geology of the Fiji Islands, etc.," *ibid.*, Vol. XXXVIII (1900), p. 34.

> Most of the raised limestone reefs of Lau are distinctly raised atolls, notably Tuvuthá, of which the old lagoon floor is about 350 to 400 feet now above sea-level and about 200 feet below the general level of its well-defined rim.[20]

Davis' interpretation of Tuvuthá as an elevated atoll is based mainly on the work of the late Dr. W. G. Foye, who visited the island in 1915. Foye himself did not refer to the island as an atoll, although he said: "Coral heads in place appear from top to bottom of the 590 feet of limestone; and in such relations that subsidence is the most logical explanation of their position."[21] Foye's map shows two masses of igneous rock, one an elongate ridge in the center of an interior basin. He also stated that the greater part of the limestone is coral and shell rubble which surrounds occasional coral heads. He found that the limestones throughout the greater part of the island rest unconformably on the andesite, and this is one of his chief contributions. Davis used this information to support the subsidence theory.

Our work in Tuvuthá convinces us that the limestone is largely, if not entirely, a rubble limestone. In its formation corals played a relatively unimportant part. The association of organisms peculiar to coral reefs is not present. Furthermore, instead of a single lagoon-like depression, there are three depressions of approximately equal size. These are separated from each other by well-defined ridges. The depressions are obviously the result of subaërial erosion, chiefly solution.

It is thus interesting to note that, of the geologists who have actually seen Tuvuthá, not one has stated that the island represents an elevated atoll. This interpretation has been advanced only by those who have obtained their information second hand.

Many other islands in Lau do have a distinct basin shape. Their highest points lie along a rim that drops to the sea in nearly vertical cliffs. Inside this rim each island is basin-shaped. Physiographically, an island of this type looks exactly as a modern atoll would look if it were elevated above sea level. Like Tuvuthá, such islands have been described as uplifted atolls; but, with one or two possible

[20] T. W. E. David, *ibid.*, Preface, pp. 9–10.

[21] W. G. Foye, "Geological Observations in Fiji," *Proc. Amer. Acad. Arts and Sci.*, Vol. LIV (1918), p. 58.

exceptions, they cannot properly be so interpreted. An examination of more than a dozen of them shows that the basin shape is developed regardless of the structure, age, or organic composition of the limestones. The basin shape is even typically developed on islands that appear to be composed entirely of bedded Tertiary foraminiferal limestone—limestone that never had any connection with a coral reef. The central depression is to be explained by unusual land drainage and solution. Undercutting by the sea, coupled with the collapse of caverns along the outer margin of the limestone mass, accounts for the steepness.

Additional evidence in support of this interpretation is obtained from small clusters of islets encircled by wide barrier reefs. Islets of this type (such as those of Yangasá and Aiwa) have been interpreted by Darwin's supporters as remnants of former atolls. Yet an examination shows that each of these supposed atoll remnants has its own basin shape—a fact difficult for the supporters of the subsidence theory to explain.

On many islands the limestones are so altered by solution and recrystallization that it is difficult to say whether they were ever a part of a coral reef or not. In general, such limestones lie well above the volcanic contact. In many instances they form the higher portions of the islands, but there are some notable exceptions. In these altered limestones molds of corals may be found here and there; but many foraminifera and other organisms also occur, and many of the rocks are bedded. A coral reef itself should not show bedding, though the elongated molds of flat reef corals may give a pseudo-bedding to a cliff section. Some sections of the altered limestones show much detrital material, and such rocks probably represent lagoon deposits. We hope to learn a great deal more about all of the limestones from a laboratory study of large numbers of thin sections.

There are uplifted coral reefs in Lau, particularly on the islands of southern Lau. Some fairly well-preserved sections show true reef structure. Corals form the bulk of the rock—flat reef colonies all shingled over one another, in position of growth and intimately associated with banded structures that probably represent the cementing algae. These uplifted reefs, however, are thin and, with one

possible exception, do not exceed 200 feet. On the island of Namuka such elevated reef limestones lie above bedded foraminiferal limestones.

It is unfortunate that so many of the published descriptions and interpretations of Lau's elevated limestones are based entirely on a study of hydrographic charts or, at best, on observations made during brief visits. The typical limestone islands are a maze of pits and crags, heavily forested. Even though an island be small, it is impossible to examine it thoroughly in one or two days' time. On the island of Ongea Levu, which is less than 5 miles long, one of us worked a full week before discovering the first of several outcrops of a Tertiary foraminiferal limestone.

There seems to be a growing feeling among geologists, particularly those who have never worked on coral reefs, that Davis in *The Coral Reef Problem* wrote the closing chapters on this long-drawn-out discussion and that Darwin's theory of subsidence has at last been proved to be correct. This is far from being the truth. The problem is still an unsolved one and will only be solved after detailed work, both geologic and biologic, on a number of key islands has been accomplished.

Davis' book is in many respects an admirable one. He brought together available information on practically every island group and mainland area which has a bearing on the problem. He explored the literature carefully and picked out what he believed to be the important points for consideration. He, himself, in 1914, traveled extensively in the Pacific, and later in 1923 visited the Lesser Antilles of the Atlantic. Indeed, he traveled too extensively, considering the time at his disposal, and was not able to stay in one place long enough to work out its entire history.

The islands considered above should illustrate the importance of the biologic factors involved in the coral-reef problem, particularly in the case of islands possessing elevated reefs. Much essential information on living reefs, which must be fitted into any theory of reef formation, has been obtained by biologists. Setchell and Howe have demonstrated the importance of calcareous algae in reef structure. Mayor, Crossland, Gardiner, Yonge, and many other biologists have added materially to our general knowledge of this complex problem.

In the report of the Standing Committee on the Oceanography of the Pacific, T. Wayland Vaughan, the chairman, writes:

> The structures called "coral reefs" are complex phenomena, built primarily through the activity of organisms which extract calcium carbonate and smaller quantities of magnesium carbonate from sea water. The problem, or the complex of the problems, is, therefore, initially a biological problem, and it may be further characterized as a problem of ascertaining those conditions in the sea favorable for the physiologic activity of reef-forming organisms.[22]

This committee has made preliminary plans to attack the coral-reef problem by an intensive study of the reefs of the Society Islands. A tentative outline shows that the work should be geologic, physiographic, chemical, physical, and biologic.[23]

Probably no single reef theory will explain all reefs. Certainly, recognition of the complexity of the problem is essential to its solution. It does not belong within the realm of any one subject, but requires the attention of scientists of many fields, each contributing his share.

[22] T. Wayland Vaughan, "Corals and Coral Reefs of the Pacific," *Proc. 5th Pacific Sci. Cong.* (1933), p. 344.

[23] *Ibid.*, pp. 252–53.

REVIEWS

Geology of Natural Gas. A symposium by HENRY A. LEY. Tulsa, Okla.: American Association of Petroleum Geologists, 1935. Pp. xii+1227; figs. 259. $6.00 ($4.50 to members of the Association).

This thick volume consists largely of thirty-four factual papers describing the geology of natural gas occurrences of North America, distributed as shown in the accompanying table.

No. of Papers	Region	Pages	No. of Papers	Region	Pages
3.....	Canada	112	8.....	Mid-Continent	266
1.....	California	108	4.....	Gulf Coastal Plain	136
1.....	Northern Intermontane Plateaus	24	5.....	Eastern Interior	110
7.....	Rocky Mountains	140	4.....	Appalachian	100
			1.....	Mexico	14

In addition are four papers, two on valuation and estimation of reserves, one on non-combustibles, and a general one of seventy-seven pages by the editor. A seventy-seven–page index fittingly completes this manual, first proposed by Sidney Powers and F. H. Lahee. None of it, except the papers on the Amarillo and Richland areas, has appeared before. Most of the manuscripts were submitted early in 1932 and revised some two and one-half years later.

This work of manifestly high though of necessity varying quality, a publication to be compared favorably with *Structure of Typical American Oilfields*, is indispensable to all geologists engaged professionally in this field the world over. The publisher's blurb lists under twenty-two headings those for whom the book is "of outstanding value." Readers of this *Journal* generally will be interested in at least some of the random quotations (in part paraphrased) given in the following paragraph.

There are no known geologic reasons why the recent high levels of natural gas production cannot be maintained for many years. . . . . The present combined daily open-flow capacity of commercial gas wells in the important proved and producing areas of the United States exceeds 55 billion ft.^{3} About 4.278 billion ft.^{3} of gas were consumed daily in the United States in 1933. Estimated future recoverable gas from commercially proved and important areas is not

less than 75 trillion ft.^{3}, of which 34 are in California. . . . . The analyses of natural gases in Alberta when arranged according to geologic horizons and localities appear to show an increase in the proportion of higher hydrocarbons to methane in a westerly direction for a given gas-bearing horizon. This may be due to the effect on the source material of increasing metamorphism westward. . . . . The largest known gas field is in the Texas Panhandle, where there is a belt of productive gas territory more than 200 miles long and 5 to 40 miles wide. It is thought to have originally contained 16.1 trillion ft.^{3} of gas, of which some 21 per cent was removed by the end of 1932. At this time about 1 billion ft.^{3} were being produced daily, nearly one-half of which was absolutely wasted, after removing the gasoline. At this rate, the supply should last through 1975 or thereabouts. . . . . All of the known oil and gas of southern Oklahoma *may* have accumulated since Comanche time, but some of it [*sic*] could not have accumulated before that period. . . . . There are at least 8 coal horizons in the Lower Pennsylvanian (Smithwick and Marble Falls) of the Bend arch of Texas. These occur below shales and above limestones or sandstones. The next to lowest of these has a carbon ratio of 69.8 in S.E. Stephens Co. and it is estimated that oil production from this general horizon in the Brazos pool comes from 81 carbon ratio strata. . . . . It is generally believed that more natural gas has been wasted to the atmosphere and lost underground by water-trapping than has been marketed.

Among the forty-seven authors it may be invidious to mention any one specifically. But no doubt considerable credit is due the editor, as there are many evidences that he has done a painstaking job, in addition to which he contributed four of the papers (one under joint authorship).

D. JEROME FISHER

Geography and Geology of the Region Including Cape Cod, the Elizabeth Islands, Nantucket, Marthas Vineyard, No Mans Land and Block Island (*Massachusetts*). By J. B. WOODWORTH and EDWARD WIGGLESWORTH. Museum of Comparative Zoölogy, Harvard College, Memoir LII. Cambridge, 1934. 23 figs.; 37 pls. (inc. maps).

The handsome volume by the late J. B. Woodworth and Edward Wigglesworth records the elaborate researches by Woodworth begun in the nineties and carried on intensively in 1914 and 1915. The geology of the whole region and each of its six natural subdivisions is discussed.

Students of the Cretaceous and Tertiary will find full details of this northern continuation of the Atlantic Coastal Plain. Glaciologists will revel in the elaborate treatment of the glacial deposits. Here multiple glaciation, still disputed in New England, is established. The Long Island

sequence is followed; and the pre-Gardiners deposits, deformed by ice-shove, are considered to represent the Nebraskan and Kansan glacial stages. A confirmed skeptic might possibly claim that the evidence for two glacial stages is scanty, but no one can deny that the Moshup till represents a strong and ancient glacial advance. Nor can the careful tracing and description of the Gardiners clay be interpreted except as representing a substantial interglacial marine invasion. The triplet, gravel, till, and gravel of the Manhasset formation overlies the Gardiners. These and older deposits are deformed and were eroded to a ridge-and-valley topography in the Vineyard interval of erosion. This interval precedes deposits regarded as Wisconsin, and the Manhasset is thus Illinoian. Reviewing the whole sequence, there is established a pre-Gardiners glacial stage (probably two, as held by the authors) and a post-Gardiners stage. The interpretation of the Wisconsin episode is elaborate and ingenious. Here Woodworth establishes a lobate distribution and more or less independent movement of the several lobes. This great advance in knowledge probably transcends in importance the other contributions in regard to Wisconsin events. Woodworth was a keen observer, and the careful reader will find that he perceived many anomalies which he explained away and which, if emphasized and restudied, will lead to other interpretations of the events of the last glacial stage.

The handsome form of this volume we owe to Dr. Wigglesworth's devotion to Professor Woodworth's memory, to the generosity of the Penrose Fund of the Geological Society of America, and to the interest of the Museum of Comparative Zoölogy. All who knew Professor Woodworth will rejoice that this modest geologist should have his last work published so completely and elaborately.

KIRK BRYAN

Sobre la presencia de restos de la flora de "Glossopteris" en las Sierras Australes de Buenos Aires. By HORACIO HARRINGTON. "Revista del Museo de la Plata," Tomo XXXIV. Buenos Aires: Casa Editora "Coni," 1934. Pp. 303–38; figs. 3; pls. 4.

This study of the late Paleozoic glacial beds and the Glossopteris flora in the southern folded ranges of the Province of Buenos Aires is of general interest because of the correlations which the author makes with South Africa, India, and Australia. In eastern Argentina the folding preceded the glaciation, whereas the folding of the Cape Mountain system of Africa occurred after the glaciation. The sierras of Buenos Aires

are much older than the mountains of the Cape, which to the reviewer is significant in view of the theory which holds these ranges to be separated portions of the same orogenic belt.

The problems of glaciation and floral migration are well handled and the floral remains are described in detail with the help of plates.

R. T. C.

Introduction aux études minières coloniales. Publication of the Bureau d'Etudes Géologiques et Minières Coloniales. Paris: Société d'Editions Géographiques, Maritimes et Coloniales, 1934. Pp. 349; figs. 25; pls. 5. Fr. 36.

In this volume is published a series of lectures designed to make better known the mineral resources of the French colonial possessions and to aid in their development and utilization. The treatment throughout is sufficiently clear and simple to be within the grasp of the intelligent layman. A list of the chapters will indicate the general scope of the volume: principal types of deposits, by L. de Launay; phenomena of surface alteration of aluminous silicate rocks in tropical countries, by A. Lacroix; practical studies of alluvial deposits, by L. Thiebault; consideration of geophysics, by C. Schlumberger; organization of a mining enterprise, by P. Lecomt; hygiene of mining, by P. N. Bernard; question of transportation, by M. Maitre Devallon; relations with the natives, by G. Hardy; microscopic study of coals, by André Duparque; microscopic study of metallic minerals, by J. Orcel; commercial questions pertaining to nonferrous metals, by Jean Faye; and relations between countries and their colonies in regard to metallurgical products, by A. Lambert-Ribot.

R. T. C.

Géologie appliquée. By E. RAGUIN. Paris: Mason & Cie, 1934. Pp. 403; figs. 110. Fr. 38.

Géologie appliquée is a brief, concise outline of the fundamental principles of geology and their practical application. The volume is conveniently divided into two parts. The first, which is composed of four chapters, outlines briefly the major fields of geology; the second, composed of nine chapters, applies the principles of pure geology to cartography, earth structure, construction work, mining, and geophysical prospecting.

The book is addressed to those employed in fields in which geologic

problems arise and to beginning students of applied geology who desire a survey of the field, rather than to the expert geologist. For the most part, the discussion can be readily grasped by the average reader, but it is doubtful whether certain sections, especially those dealing with crystallography and optical mineralogy and petrology, are sufficiently elementary to be clear to those not already versed in the subjects.

E. C. OLSON

The Story of Diamonds. By A. C. AUSTIN and MARION MERCER. Chicago: Chicago Jewelers' Association, 1935. Pp. 96; with 125 illustrations. $0.50.

This little book is an outgrowth from the diamond mine and diamond exhibit at the recent Century of Progress Exposition. Its aim is to present in a non-technical form the nature and occurrence of diamonds, historic and geologic; the methods of mining and cutting diamonds; their uses in industry; together with historical descriptive accounts of some of the most famous diamonds. The book contains much useful information and is very interesting reading.

R. T. C.

"Glacial Deposits outside the Terminal Moraine in Pennsylvania," by FRANK LEVERETT in *Pennsylvania Geological Survey Bulletin G7* (1934), 4th ser. Harrisburg: Bur. of Publications, Dept. of Property and Supplies, 1934. Pp. 119; figs. 38; pls. 2. $0.50.

The investigations on which this report is based were made during the field seasons of 1926, 1927, and 1928. A brief discussion of the results prepared by Dr. Leverett has appeared in an earlier bulletin (G. H. Ashley, "Scenery of Pennsylvania," *Pa. Geol. Surv. Bull. G6*, 1933). A more comprehensive report on the studies in northwestern Pennsylvania will probably appear later as a *Professional Paper* of the United States Geological Survey.

Although some revision is made of the boundary of the Wisconsin drift, attention is directed chiefly to the pre-Wisconsin glacial deposits found in (*a*) the Susquehanna Valley, (*b*) the Delaware Valley and eastern New Jersey, and (*c*) northwestern Pennsylvania. In each of these regions the position and character of the Wisconsin, Illinoian, and pre-Illinoian tills and outwash are discussed in detail. Reference is also made to drainage changes and to the relation of glacial deposits to the gravels of the Coastal Plain.

The existence of pre-Wisconsin drift in northwestern Pennsylvania was established by Leverett in 1902 and was then referred to the Kansan. In the present study "Illinoian" and "Pre-Illinoian" deposits are recognized. The presence and extent of the older drift in eastern Pennsylvania and its relation to that in New Jersey are here considered for the first time. The fact that most of the outlying drift in eastern Pennsylvania is Illinoian, whereas that in New Jersey is older, probably accounts for early variance of opinion regarding age. Both older drifts are usually less than 50 feet thick and show thinning on the uplands and thickening in the valleys. The thorough leaching and patchy occurrence of the older till serve to distinguish it from the Illinoian which, although oxidized to depth of 30–40 feet, still retains morainal forms. The age of the pre-Illinoian drift is undetermined and there is a possibility that two ice advances were involved. This is suggested by the erosional interval between the pre-Illinoian Bridgeton and Pensauken gravels of New Jersey, both of which carry rocks of seemingly glacial derivation.

LELAND HORBERG

"The Cambrian-Trias Sequence of Northwestern Kashmir (Parts of Muzaffarabad and Baramula Districts)" by D. N. WADIA in *Records of the Geological Survey of India*, Vol. LXVIII, Part II. Calcutta: Geological Survey of India, 1934. Pp. 176; figs. 6; map in colors.

In contrast to southeastern Kashmir, the northwestern part of the state is characterized by a remarkably full development of the Cambrian system. A break in the stratigraphic column from the top of the Silurian to the end of the Middle Carboniferous indicates a long mid-Paleozoic land period. The Agglomerate Slate (Talchir) series is placed in the Upper Carboniferous. In this area the Panjal volcanic period extended from the Uralian to the beginning of the later Triassic.

R. T. C.

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